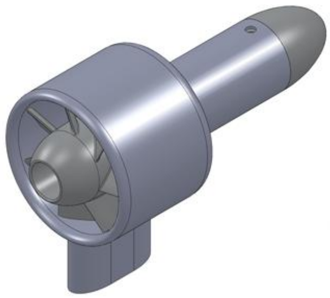

ICEPICK

BLDS Heating

Senior Project June 2011

Mechanical Engineering
California Polytechnic State University, San Luis Obispo

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Statement of Disclaimer

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Executive Summary

Dr. Westphal, a professor at Cal Poly San Luis Obispo, created a boundary layer data system (BLDS). This device was designed to measure the boundary layer over a wing of an airplane during flight. A problem with the BLDS is that at flight altitude of 50,000ft, the BLDS stops functioning due to the extremely low temperatures.

Team IcePick's objective was to design, build, and test a device which could provide heat to the BLDS so it can function. Our team decided to continue with where the previous senior project team had left off and build upon their proof of concept design. Our sponsor, Dr. Westphal, allowed our team to explore two avenues for manufacturing the device: casting and machining. While casting our first prototype, our team learned this method was more suitable for more advanced casting processes which were not readily available to our team; this method of manufacture was abandoned before a final prototype was made. We were able to produce a working metal prototype using CNC machining. This prototype was then tested in the Cal Poly Wind Tunnel to investigate what the highest power output could be and to determine the resistance which produces max power output at design conditions. While our test results showed that our device produces less power then what we were aiming for, our team believes the device does produce enough power to allow the BLDS device to work in a wider temperature range than before.

The following report goes into detail explaining our team's design and manufacturing process and the results gathered from our testing.

Chapter 1: Introduction

The Boundary Layer Data System (BLDS) is a device created by Dr. Westphal which measures the boundary layer over the wing of an airplane during flight. The unit is self-contained with batteries and solid state storage, and can be attached with adhesive to the wing of an airplane with no modification to the airplane. Due to the high altitudes at which it operates, the BLDS is subject to extremely cold temperatures which cause the sensors to output inaccurate measurements. The goal of this project is to design, build, and test a device which can be mounted on the wing of an airplane and heats the BLDS within the operating temperature of its components. Funding for this project comes from a grant provided by the Northrop Grumman Corporation, and our contact for this project is Dr. Russell Westphal.

A self-contained unit to heat the BLDS is necessary because tapping into an aircraft's power system would involve penetrating the skin of the airplane and would require the aircraft to be reapproved for flight. The self-contained aspect of the BLDS also makes it portable so it can be used on any aircraft without requiring any modification to the airplane.

This project is a continuation of a previous senior project which was completed in December of 2009. The previous group had manufactured a plastic rapid prototype proof of concept which successfully produced power in Cal Poly's wind tunnel. It is our goal to turn this proof-of-concept into a prototype capable for flight.

The primary objective of Team IcePick was to design, build, and test a flight capable prototype which can heat the BLDS up to temperatures at which it operates reliably. Since our team was provided a working proof of concept from Team AeroRAT, we worked with their existing design, modified it to make it manufacturable, and verified it met all of our requirements. We also analyzed the stresses in the device in order to use minimal material to decrease weight while ensuring the device would remain robust.

Chapter 2: Background Information

The previous group, Team AeroRAT, selected a micro Ram Air Turbine (RAT) as the method of generating power. Larger RATs are currently used as backup power systems in most military and commercial aircraft and they typically are designed for emergency use only. The rotors for these devices are usually around three feet in diameter. Other than the proof of concept from the previous senior project, no other RATs at a small enough scale exist. Some small turbine motors exist, however they were designed to burn fuel to produce power not harness wind energy to produce power.

Most of the requirements for this project are based on the flight conditions of the airplane on which the device will be mounted. The outside air temperature is below -60°C and the max onset velocity is 350ft/s. Dr. Westphal has requested that the BLDS be kept at around -20°C by the heating device. The previous group estimated that 50W of power would be necessary to achieve this. This estimate was similar to another estimate performed by an engineer at Northrop Grumman.

After determining the requirements and selecting the method of power generation, the previous group built an array of turbine blisks with varying geometries and tested all of them to find the blisk which produced the maximum power. The rotor which was selected has a 35° blade angle and a projected power output of 65W at the max onset velocity of 350 ft/s. Since the estimated power required to heat the BLDS is 50W, this rotor was selected for the final concept.

In additional to designing a rotor, Team AeroRAT also designed a cowling and a support. The purpose of the cowling was for two reasons. First, the cowling protects the thin blades of the turbine blisk when the device is handled. Second, the cowling protects the plane in the event that the blisk should shatter. Instead of the blades flying in an unpredictable direction and possibly striking the plane, the cowling directs the blades out the back, in which case damage to the plane is unlikely. The mount which was designed consists of two struts which support a curved surface onto which the shroud is mounted.

Professor Westphal has recommended that the device be made out of aluminum. In addition to aluminum being a preferred material in the aerospace industry, there is a large pool of information on the properties of aluminum. An excellent resource for this is *Aluminum and Aluminum Alloys* by Joseph R. Davis, which includes information on Aluminum at extremely low temperatures.

Another resource Team IcePick utilized was the project's Sponsor, Dr. Westphal, who is very knowledgeable on the background of this project and willing to help us obtain any information needed. Also Team IcePick's lab advisor, Mr. Fabijanic, was a good resource and helped us obtain and understand information on unknown topics. Team IcePick did not rely on these professors but did use them to help guide the team in the right direction for obtaining information.

Testing was performed in a wind tunnel to measure the power output of the device. There is a wind tunnel available at Cal Poly which was used to perform testing at limited wind speeds, and the possibility of using the facilities at Northrop Grumman to perform a full scale test was proposed as well. Cal Poly also has a freeze chamber which could be used to test the turbine statically at low temperatures; however there was no good laboratory setting available for Team IcePick to test the turbine at extremely low temperatures and high wind speeds for extended periods of time. The only viable possibility is to test the device in actual flight.

Chapter 3: Design Development

We used Quality Function Deployment (QFD) to determine the parameters which are most important to the design of this device. QFD is a tool which helped us take customer requirements and translate them into engineering specifications. Our QFD chart for this project can be seen in Appendix A. After completion of the QFD chart, our group was able to determine the engineering requirements for our device. The engineering requirements can be seen in Table 1 with a corresponding legend in Table 2. Table 1 displays information on each parameter which we have formulated as an engineering requirement. In the table we have a target; tolerance; risk of meeting the engineering target; and how we plan on verifying the design requirement, compliance; for each parameter.

Table 1. BLDS Heating Device Formal Engineering Requirements

Spec. #	Parameter Description	Target (units)	Tolerance	Risk	Compliance
1	Internal temperature of BLDS	-20 °C	± 20 °C	H	T, S, A
2	Operating altitude	50,000 ft	Max	L	T
3	Outside air temperature	-60 °C	Max	L	T
4	Max onset velocity	350 ft/s	Max	M	A
5	Power output from turbine	50 W	Min	M	T, S, A
6	Weight	1 lb	Max	M	T, S, A
7	Component drag force	TBD	TBD	L	T, A
8	Total lifetime	TBD	TBD	L	A

Table 2. Legend for Table 1

Risk Assessment	Compliance Verification Factors
H = High Risk	A = Analysis
M = Medium Risk	S = Similarity to Existing Design
L = Low Risk	T = Test

Weight was an important aspect of our design. The absolute maximum weight for the device is one pound, but it was desirable to minimize the weight as much as possible. If the weight of the RAT and the BLDS together is less than one pound, then the RAT can be mounted on the BLDS. This shortens test set up time for the BLDS since it can be mounted on the plane as a single device. If the weight of the BLDS and the RAT is greater than one pound, then the RAT and the BLDS must be mounted separately. There are two configurations for the BLDS, one with a stage which weighs nearly one pound, and one stageless which weighs about half a pound. Our goal was to make the RAT mountable on the stageless BLDS which requires our device to weigh less than half a pound.

Our system had to be designed to work in standard flight conditions, which are altitudes up to 50,000 feet and a minimum outside air temperature of around -60°C. The max onset velocity is 350 ft/s. This velocity will determine the forces acting on the device and will determine how sturdy it needs to be. Since the BLDS device can only be flown on flights with no condensation, we can safely assume our device will not be operated in conditions where condensation is present. Due to the extremely cold temperatures, our device must produce approximately 50 watts in order to provide enough power to heat the BLDS. This maintains the sensors, batteries and microcontroller in their operating range.

Due to the small size of the BLDS heating device compared to the airplane, we assumed that the micro RAT drag force was small enough that it would not affect flight in any way.

Our team began our design development with a choice between using the feasibility design created by the previous senior project team, Team AeroRAT, and creating a new design. Since our sponsor's main goal was to have a metal product which can be flight tested at the end of this project, our team decided to continue with the previous senior project design. With this in mind, we broke down the components in Team AeroRAT's design to see where we could improve their design to better achieve meeting the requirements set by our sponsor. Our team broke down the proof of concept into eight components, which would determine our top design. These components were the blisk, cowling, generator, mount, heater, method of manufacturing, controller, and insulation. We then took each component and used a decision matrix to decide how to proceed with each in our top design. A decision map is shown in Figure 1, which breaks down our decision making process.

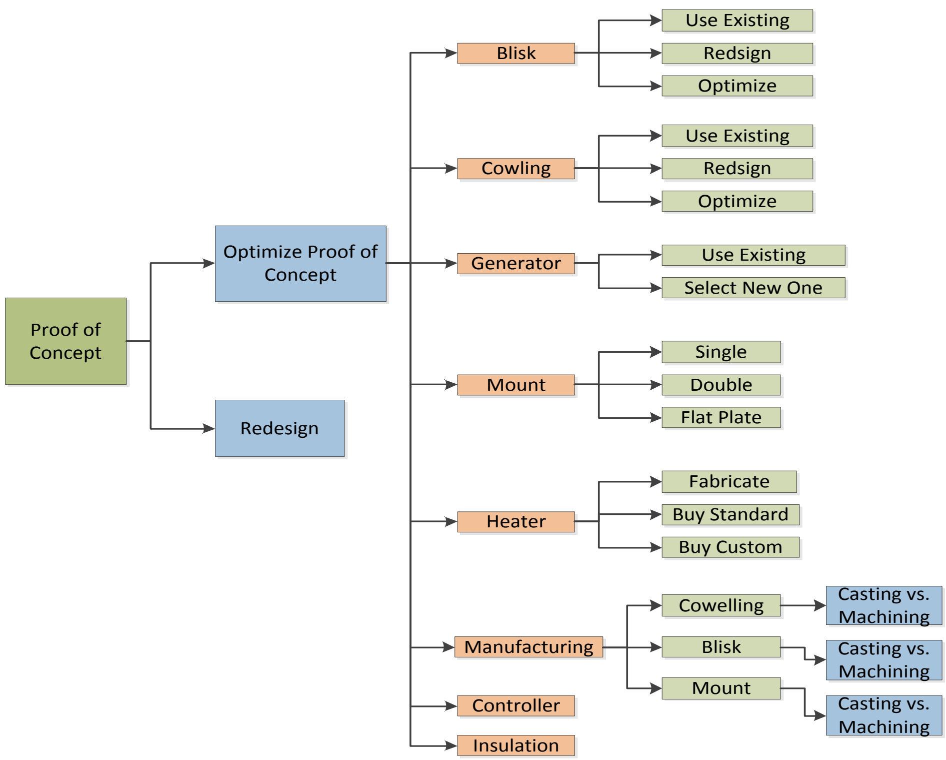


Figure 1. Decision map from Fall quarter, 2010.

The first decision matrix our team created was for the blisk. This decision matrix is shown in Table 3. Our team had three possible options for the design of the blisk: to use the existing design, create a new design, or modify the existing design. The design criteria we used for determining which option to use was: cost, effectiveness, size, time to design, time to manufacture, and weight. The biggest factor which contributed to our team's decision was the time to design. None of the members in Team IcePick had any experience dealing with design and analysis of turbines, so we made the decision to keep the existing design in order to save time.

Table 3. Decision matrix for the blisk.

		Design Criteria						
		Cost	Effectivness	Size	Time to Design Model	Time to Manufacture	Weight	Overall Satisfaction
	Weighting Factor	0.05	0.15	0.10	0.50	0.10	0.10	1.00
Alternatives	Use Existing Design	100% / 5%	75% / 11%	75% / 8%	100% / 50%	90% / 9%	90% / 9%	92%
	Create New Design	85% / 4%	80% / 12%	85% / 9%	40% / 20%	90% / 9%	90% / 9%	63%
	Modify Existing Design	85% / 4%	90% / 14%	90% / 9%	60% / 30%	90% / 9%	90% / 9%	75%

The next component for determining the final design of the micro Rat was the cowling. The decision matrix for the cowling is shown in Table 4. Team IcePick had three possible options for the design of the cowling: to use the existing design, create a new design or modify the existing design. The design criteria we used for making our final decision was: weight, time to design model, manufacturability and chance of success. We decided to modify the design of the cowling because we determined that through modification of the cowling, weight could be reduced and manufacturability could be improved without sacrificing performance.

Table 4. Decision matrix for the cowling.

		Design Criteria				
		Weight	Time to Design Model	Manufacturability	Chance of Success	Overall Satisfaction
	Weighting Factor	0.50	0.05	0.10	0.35	1.00
Alternatives	Use Existing Design	75% / 38%	100% / 5%	10% / 1%	100% / 35%	79%
	Modify Existing Design	90% / 45%	70% / 4%	90% / 9%	90% / 32%	89%
	Create New Design	90% / 45%	10% / 1%	90% / 9%	50% / 18%	72%

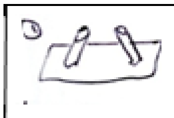
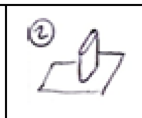
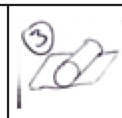
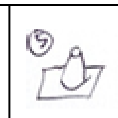
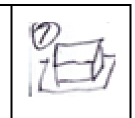
A decision matrix was made for the generator to decide if a new one should be purchased or if we should select a new one, the decision matrix is shown in Table 5. The design criteria we used for making our decision was: weight, cost, power output, time to select, and chance of success. The design matrix resulted with a slight preference towards purchasing a new one.

Table 5. Decision matrix for the generator.

		Design Criteria					
		Weight	Cost	Power Output	Time to Select	Chance of Success	Overall Satisfaction
	Weighting Factor	0.40	0.10	0.40	0.05	0.05	1.00
Alternatives	Use Existing	75% / 30%	75% / 8%	75% / 30%	100% / 5%	100% / 5%	78%
	Select New	75% / 30%	75% / 8%	90% / 36%	50% / 3%	50% / 3%	79%

For the mount, we used a Pugh matrix to determine the design which would best meet the requirements our sponsor had set for our team. We came up with seven possible solutions and six different criteria to distinguish the best design. In our Pugh matrix, we used the previous design from Team AeroRAT as the datum and weighed the advantages and disadvantages of the other designs. Our Pugh matrix can be seen in Table 6. Team IcePick determined that our second option, a single pillar base mount with an elliptical shape, would be our best design to meet the requirements. We found that it would be easier to manufacture, was able to better integrate with the cowling, and it would be easier to install than the previous design.

Table 6. Pugh matrix for the mount.

							
Weight	D	S	+	S	-	S	s
drag		S	+	S	S	-	-
Manufacturability	A	+	+	+	+	+	+
Installation case		+	-	+	+	s	+
Integration with cowl	T	+	-	S	S	s	+
integration with mount		+	-	+	+	+	+
∑ +	U	4	3	3	3	2	4
∑ -		0	3	0	1	1	1
∑ S	M	2	0	3	2	3	1

We used a decision matrix to determine how to obtain a heater to use in our design. The decision matrix for the heater is shown in Table 7. Our team had three possible options for the heater: fabricate our own, buy a standard one from a catalog, or buy a custom one. The design criteria we used for making our decision was weight, cost, lead time, durability, size, effectiveness and amount of heat produced. We decided to buy a custom strip heater in order to maximize the heater's effectiveness and amount of heat produced.

Table 7. Decision matrix for the heater.

		Design Criteria							
		Weight	Cost	Lead Time (create/order)	Durability	Size	Effectiveness	Amount of Heat Produced	Overall Satisfaction
	Weighting Factor	0.05	0.05	0.25	0.20	0.05	0.15	0.25	1.00
Alternatives	Fabricate	90% / 5%	25% / 1%	25% / 6%	85% / 17%	100% / 5%	90% / 14%	90% / 23%	70%
	Buy Standard	85% / 4%	85% / 4%	90% / 23%	85% / 17%	90% / 5%	90% / 14%	90% / 23%	89%
	Buy Custom	90% / 5%	70% / 4%	90% / 23%	85% / 17%	100% / 5%	100% / 15%	100% / 25%	93%

When we were in the design development stages of our project, we planned on manufacturing three components: the blisk, the cowling, and the mount. For each of these components we created a decision matrix to decide how to manufacture each component. These matrices can be seen in Table 8, 9 and 10. When we created these matrices, we had not done any of the casting or machining, the matrices were purely based on speculation but we had hoped that they might give our team some insight on which process would be preferred.

Table 8. Decision matrix for the manufacturing of the blisk.

		Design Criteria				
		Cost of Materials	Cost of Manufacturing	Ability to Make Design Features	Time to Manufacture	Overall Satisfaction
	Weighting Factor	0.20	0.20	0.50	0.10	1.00
Alternatives	Cast	90% / 18%	100% / 20%	100% / 50%	75% / 8%	96%
	Machine	90% / 18%	75% / 15%	75% / 38%	75% / 8%	78%

Table 9. Decision matrix for the manufacturing of the cowling.

		Design Criteria				
		Cost of Materials	Cost of Manufacturing	Ability to Make Design Features	Time to Manufacture	Overall Satisfaction
	Weighting Factor	0.20	0.20	0.50	0.10	1.00
Alternatives	Cast	90% / 18%	100% / 20%	100% / 50%	75% / 8%	96%
	Machine	50% / 10%	75% / 15%	90% / 45%	75% / 8%	78%

Table 10. Decision matrix for the manufacturing of the mount.

		Design Criteria						
		Ability to Make Design Features	Cost	Surface Finish	Time to Manufacture	Tolerance	Weight	Overall Satisfaction
	Weighting Factor	0.30	0.10	0.15	0.10	0.15	0.20	1.00
Alternatives	Machining	50% / 15%	75% / 8%	90% / 14%	60% / 6%	90% / 14%	100% / 20%	76%
	Casting	90% / 27%	90% / 9%	80% / 12%	75% / 8%	85% / 13%	100% / 20%	88%

For the controller and insulation, we did not determine which kind or type would be preferred, because they are easily available and therefore will be chosen once we have manufactured and tested our prototype.

Chapter 4: Final Design

After going through the design process described above, Team IcePick came up with two top concepts. Both were based on the design from Team AeroRAT, but several changes were made in order to save weight and simplify manufacturing. The figures below compare the proof of concept to our final concepts.

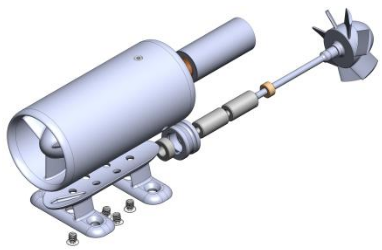


Figure 2. : Team AeroRAT's proof of concept, this was a great design to prove the possibility of using micro RATs to generate power however their design was impossible to manufacture other than using rapid prototyping methods

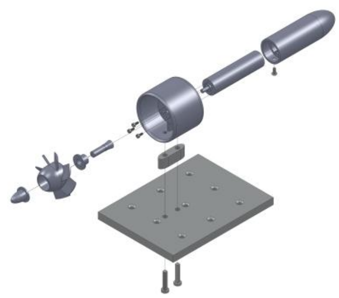


Figure 3: Team IcePick's final CNC model. This ended up being our final prototype.

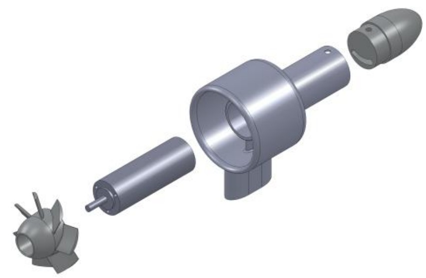


Figure 4: Team IcePick's cast model, due to limited resources available to us, we never were able to produce a final prototype using casting methods

In order to save weight, the cowl was shortened to cover only the turbine blades. We did not expect this to significantly affect the function of the device. We also removed the flow straighteners. In addition to the flow straighteners being extremely difficult to manufacture, their function was not supported by any analysis. We tested these changes to the design to ensure that the device still met all of our requirements.

For the mount, a single pillar was selected as opposed to the twin pillars proposed by the previous group. A single pillar was easier to manufacture and easier to attach to the mounting plate. Instead of having the pillar as part of the mounting plate, our concept has it as part of the cowling. Screw holes will be tapped into the bottom of the mounting pillar which will allow it to be easily attached to a mounting plate.

The rotor geometry was left unchanged, however instead of replacing the generator shaft with a shaft built onto the rotor, the rotor was attached onto the original generator shaft using a collet style propeller adapter made for a radio controlled airplane.

Although decision matrices indicated that casting was a slightly favorable method of manufacturing for the turbine cowling and blisk, Team IcePick planed on manufacturing two separate prototypes using both manufacturing methods. This resulted in two similar concepts tailored to each manufacturing method.

In the design development phase, Team IcePick decided to purchase a new generator. In order to decide which generator would be best for the turbine, Team IcePick created a list of specifications of all the generators which were small enough to be utilized in the turbine. The specifications were rated on a go/no-go basis and Team IcePick narrowed down the decision to two generators. Team IcePick decided to buy both of the generators. One was the same exact generator Team AeroRAT used in the development of their proof of concept, and the other was a smaller, lighter and higher output generator which Team IcePick had hoped to get more power generated for less weight. The complete generator decision chart can be found in the Appendix H. In order to simplify testing, a rectifier was added between the generator and the heater. This is discussed in more detail in Chapter 6: Design Verification. A wiring diagram is shown below to show how the generator and heater were wired.

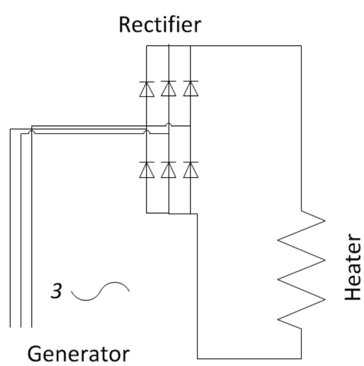


Figure 5: Wiring Diagram for the microRAT

Since Team IcePick had already decided to cast and machine the turbine and the generators had two different geometries, Team IcePick decided to use one generator for each method of manufacture. This later turned out to hurt our prototype and is discussed in Chapters 5 and 7.

Cast Design

The original concept model did not need to be modified in order to be manufactured via casting, but the casting process does limit the prototype to casting alloys. The casting model is shown below in Figure 6.

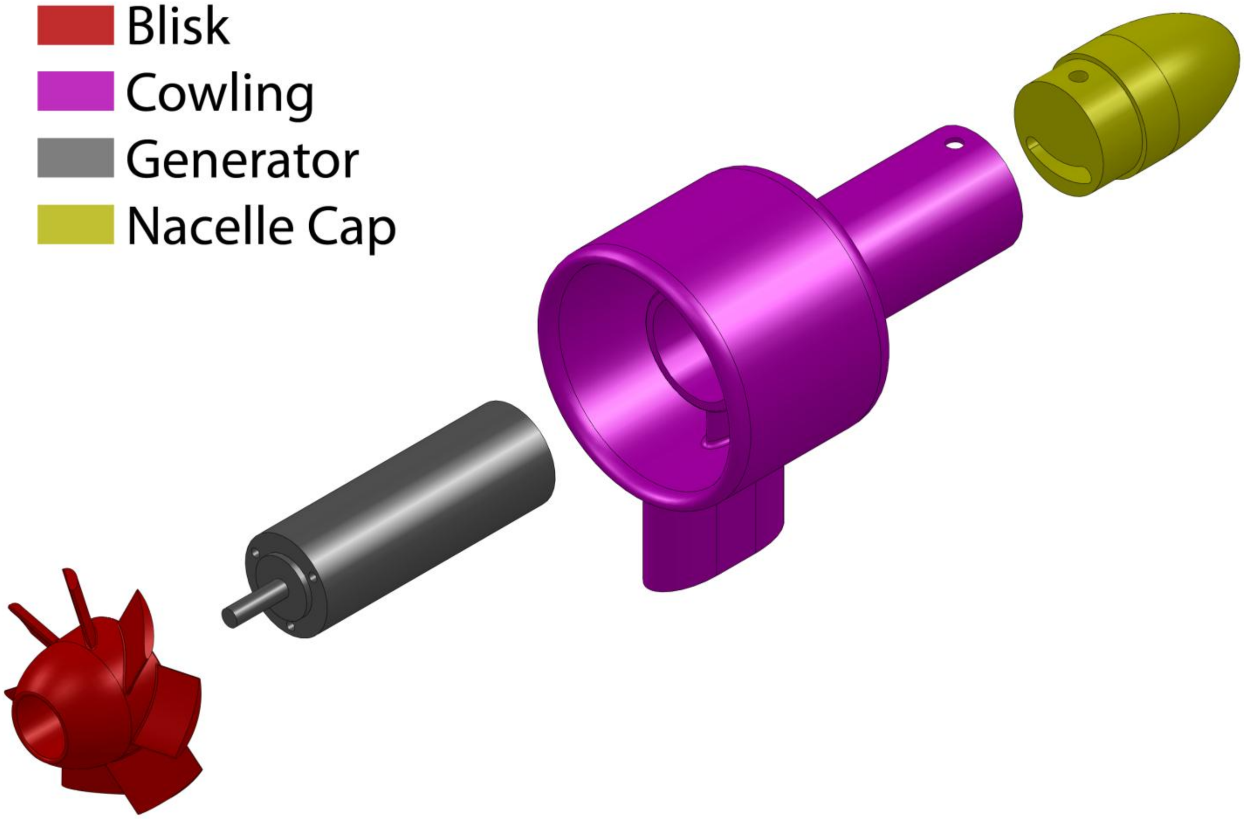


Figure 6: Exploded view of the casted model

The cap is attached with a set screw and has a route for the wires to come out the end. The wires would be doubled back and taped to the outside of the nacelle, and travel down the mounting post to the BLDS. This design requires finish machining on the critical surfaces. The inside diameter of the cowling, which the blades of the turbine spin next to, would have to be bored out to a precise dimension since there is a tight clearance between the inside of the cowling and the blades on the blisk. The hole through the nacelle would have to be drilled out since when it is cast it is a solid piece. The screw hole on the nacelle and the tapped hole on the nacelle cap will have to be machined also.

CNC Design

The CNC concept required modification to the cowling but no modifications for the blisk. The concept also required that the support strut be made separate. The CNC concept allows for a different selection of materials but would be a more expensive method of production if manufacturing in larger quantities. The CNC concept is shown below in Figure 7.

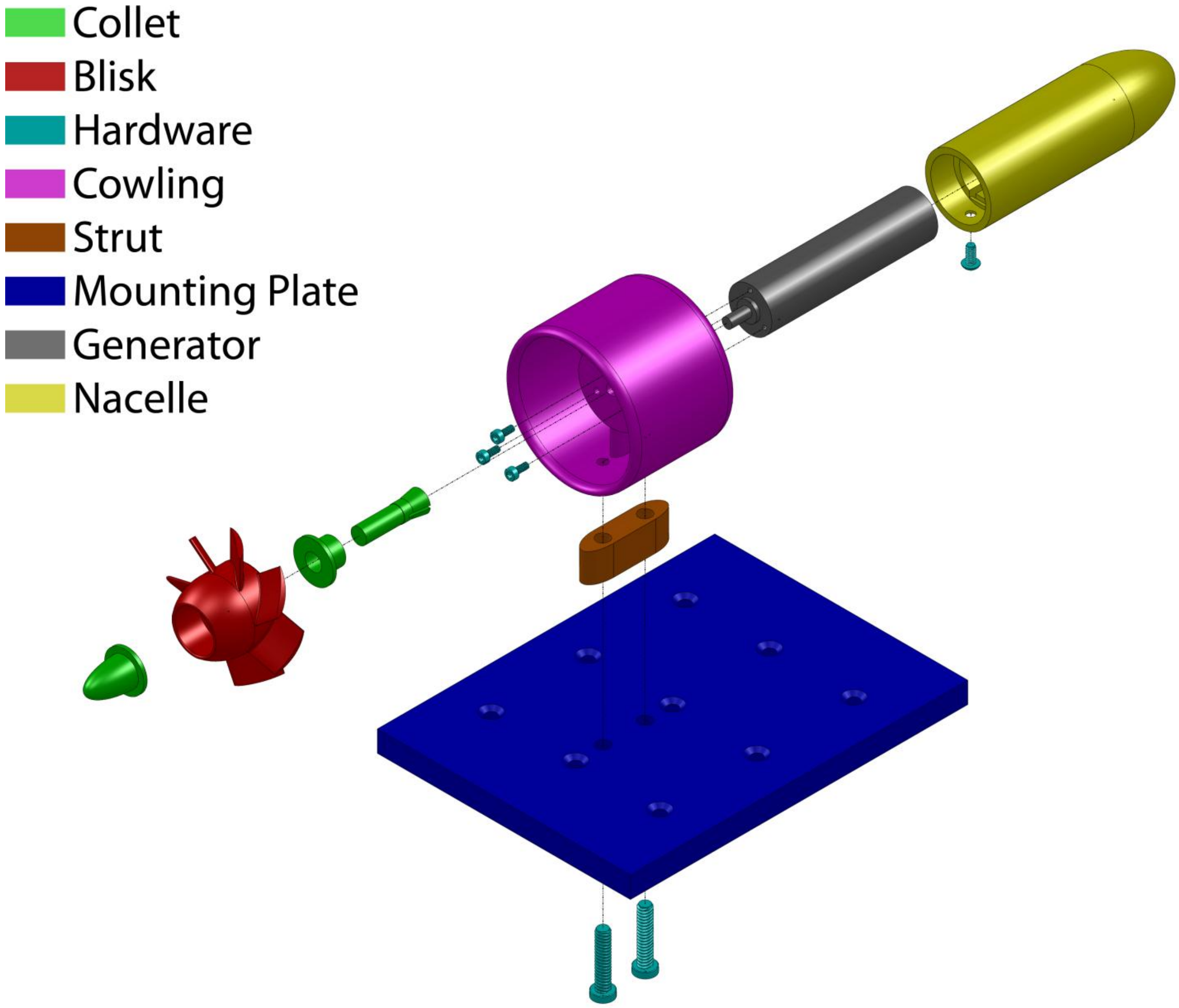


Figure 7: Concept Model for CNC Machining

All changes in geometry were made to enhance manufacturability. All fabricated items were made of 6061 Aluminum, which was chosen because it has become a standard material for structural parts in the aerospace industry.

Final Design Analysis

Analysis needed to be performed in order to verify that components would be strong enough to handle wind loading and bolt failure would not occur. Appropriate analysis was performed and the results are included below, full detailed analysis can be found in Appendix E.

Table 11. Tabulated Analysis Results

Nacelle strut safety factor	25.88
Minimum mounting bolt diameter for a safety factor of 3	.1245 in
Turbine blade root stress safety factor	5.081
Mounting plate safety factor	41.7
Support strut safety factor	63.1
Worst case total drag force	12.87 lb
Worst case thrust loading on generator	2.12 lb
Thrust loading on generator at operating conditions	.3 lb

The Nacelle strut dimensions were predetermined and Team IcePick calculated the safety factor to make sure that they would be strong enough to securely hold the nacelle between the cowling. The resulting safety factor of 25.88 was high enough to not raise any concern. While we considered shrinking them to save weight, we did not do this for two reasons. First, the size is limited by the casting process, as thinner parts are harder to cast and more prone to problems. Second, the weight savings would be minimal and we are already well within our specification of 1lb, and our target weight of < 0.5 lb.

Team Ice Pick wanted to use the smallest bolts possible to keep the support strut thickness small and save weight. A minimum safety factor of 3 was chosen and a minimum bolt diameter was calculated to be .1245 in. Team IcePick chose a #6 bolt which is slightly larger than the minimum bolt diameter, and will work well to fasten the turbine to the mounting plate.

Due to the high rotational speed the blisk was expected to reach, Team IcePick calculated the root stress the blades would experience and found a safety factor of about five. This was lower than Team IcePick had anticipated, however it was still greater than our minimum safety factor of three.

The mounting plate and the support strut safety factor were calculated to ensure there would be no unexpected failures. The safety factors were high enough to not raise any concern.

Drag force was calculated at worst case conditions of cruising speed at sea level. The thrust force that the generator would experience at these conditions was outside of the specified maximum value provided by the supplier. However, after calculating the thrust load at normal operating conditions Team IcePick concluded that the generator may have axial loading for brief periods of time that will be higher than recommended but it will not interfere with operation or success of the turbine as a whole. No other generators were found which could meet the geometric constraints and still handle the worst case axial loading which was calculated. Team IcePick concluded that there is a possibility of reduced service life of the generator, but that will not be able to be determined until after the turbine has been put into operation.

Another aspect of analysis to consider was the geometry of the forward-facing surfaces. Team IcePick decided to go with a two-to-one ellipse for all lips because this generally works for most cases. While we did consider performing actuator disk theory to design the cowling, we were advised that it would probably have negligible effect on our results so we did not perform these calculations. Since Team IcePick was expecting to meet or exceed all requirements on the creation of the first prototype, a two-to-one ellipse was the best choice for the lip sizing.

Cost Analysis

The total cost of this project was $3624.56. A total breakdown of the expenses of this project can be seen Appendix C. The expenditures, which occurred during this project, can be broken down into 5 major categories: motors, casting process, CNC process, connection pieces, and testing. For this project, our team bought two motors. The 16mm motor was the same motor used by the previous senior project team. Our team also bought a 13mm motor, which was smaller and lighter as well as had properties we felt better suited our project's needs. The total cost for the both motors is $906.79. For the casting process, our team only had one cost associated with this category: the rapid prototype models. The cost for the rest of the casting process was minimal and covered by the IME department. The total for making the CNC model was where most of the expenses of this project accumulated. Our team had to buy the aluminum stock as well as the tooling needed to make the individual parts which make up our device. However, what made this process so expensive was the hours of coding and machine time required to make each part. Just the coding and machine time alone cost $2,000 towards our project. The connection pieces, such as bolts and screws, came out to a total of $26.70. Last, in order for our team to fully analyze our results during testing, we bought a rectifier to convert the AC power to DC. The wires and other equipment needed for our team to test were provided to use by the EE and ME departments. While the initial expenses of this project are high, to make a second prototype would be far less expensive because the code for the CNC parts are already completed.

Chapter 5: Product Realization

CNC Model:

Due to the general complex geometries of most of the parts, it was decided that CNC machining would be the only way to machine the parts; the base plate was the only part that was made manually. Several iterations were required to work out all bugs in the CNC code for each part, however now that all bugs have been worked out, the code can be used to create an identical part if more are needed. Each part and its associated problems related to manufacturing are addressed below.

Cowling

The cowling was manufactured using a 3 axis CNC mill. Since the cowling had 3D surfaces on both sides, two setups were required. Square stock was used in order to maintain concentricity for both setups. Some relatively special tools were required to manufacture the cowling, such as a 1/16 ball endmill, however these same tools were required to manufacture the blisk.

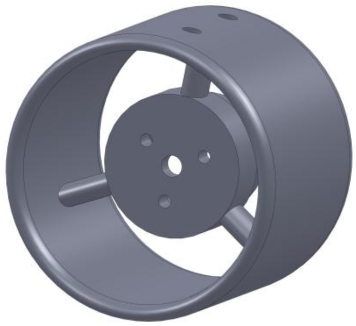


Figure 8: Front view of cowling, the first setup machined the 3D surfaces and features you can see here. Square stock was used so the machine could be zeroed for the back setup.

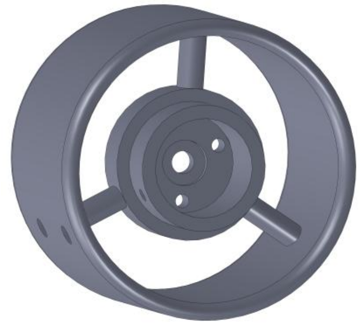


Figure 9: Back view of cowling, notice how this side also has 3D surfaces which depend on the concentricity of the features on the front

Nacelle

The nacelle was also a two set up part. The first set up involved using a CNC lathe to generate the outer geometries and the second setup consisted of putting the nacelle in a CNC mill vertically to machine out the geometries to accommodate the generator and its associated wiring. It was discovered that the CNC lathe linearly interpolated for 3D surfaces which resulted in a stepped surface for the outer geometries. These imperfections was polished out, however it is assumed that with the use of better CAM software or CNC equipment a better surface finish could be achieved without the need for polishing.

Figure 10: Side view of the nacelle. The contours on the right were machined using a CNC lathe.

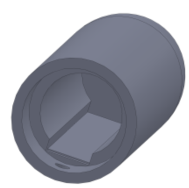


Figure 11: Front of the nacelle. A mill was required for this set up in order to machine out the square pocket which accommodates the wires of the generator

Blisk

The blisk was the most difficult to machine due to its complicated geometries. It required special tooling, special CNC programming, multiple machines, multiple setups, and it took over ten hours of machine time in order to manufacture.

The blisk consisted of three setups. First, a CNC Lathe was used to turn down the stock to the proper diameter and machine the outer contour and the curved front surface. The through hole and the pockets necessary to accommodate the collet and mounting bolts were also cut out on the lathe. Next, a 4-axis mill was used to cut out each blade. A CNC mill was then used to machine off the pocket in the back of the blisk and the completed blisk was parted off with a lathe. It was found that while machining the blades, due to the shear amount of machine time, end mills would break due to fatigue. This increased the overall cost of the blisk, however due to the resources readily available to Team IcePick, this was deemed acceptable. Figures below clarify the machining processes outlined above.

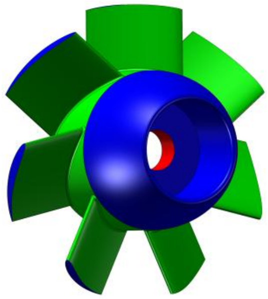


Figure 12: The blue surfaces indicate the first material which was removed in the initial CNC lathe setup.

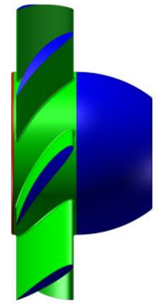


Figure 13: The green surfaces indicate the material which was removed with the 4th axis CNC mill.

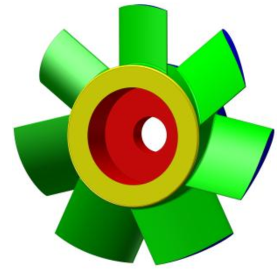


Figure 14: The red surface indicates the last and final CNC Mill set up and the yellow surface indicates the area which was parted off with the lathe.

Support Strut

The support strut was cut on a CNC mill using square stock in order to maintain nice ellipses for aerodynamics and accommodate the cowling perfectly. This was a very simple CNC part and no problems occurred during the manufacturing of this part

Mounting Plate

The mounting plate was manually made using a mill; it was a simple part requiring no special tools.

After completing the fabrication of the machined model, problems arose during assembly and testing which were not anticipated by Team IcePick. The generator which Team IcePick chose to use for the machined model turned out to be much more difficult to work with due to its short shaft length and preloaded ball bearings. The preloaded ball bearings allow the shaft to be pressed in about 3mm. This made the blisk rub against the cowling at high wind speeds, and the short shaft length prevented us from having the collet grab the shaft at an appropriate length away from the cowling to solve this problem. Figures below outline this problem.

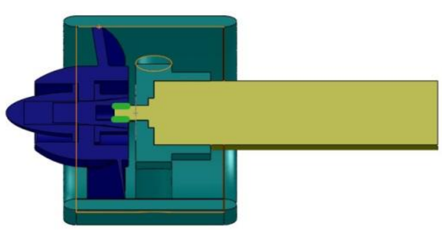


Figure 15: The preloaded ball bearing made it necessary to offset the blisk (blue) from the generator shaft (tan). The green lines represent the shaft area which the collet has available to clamp onto, in this case the area was not sufficient.

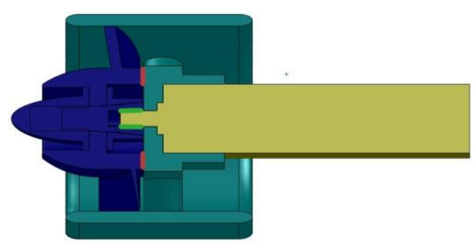


Figure 16: This figure shows the blisk securely fastened to the generator, under wind loading, the blisk (blue) is pushed back on to the cowling (teal) which causes rubbing, the areas which rub are shown with red lines. While it would seem that the simplest solution would be to modify the blisk, rather than both the cowling and nacelle, the shear complication involved with manufacturing and debugging CNC code for the blisk outweighs the simplicity of remaking the cowling and nacelle.

Cast Model

The cast model was made with the assistance of Martin Koch of the IME department. We chose an investment casting process because it provides high quality parts with a good surface finish. The first step was to add gates to the solid models. Gates provide a path for the molten metal to flow into the mold. The models with the gates are shown below in Figure 17.

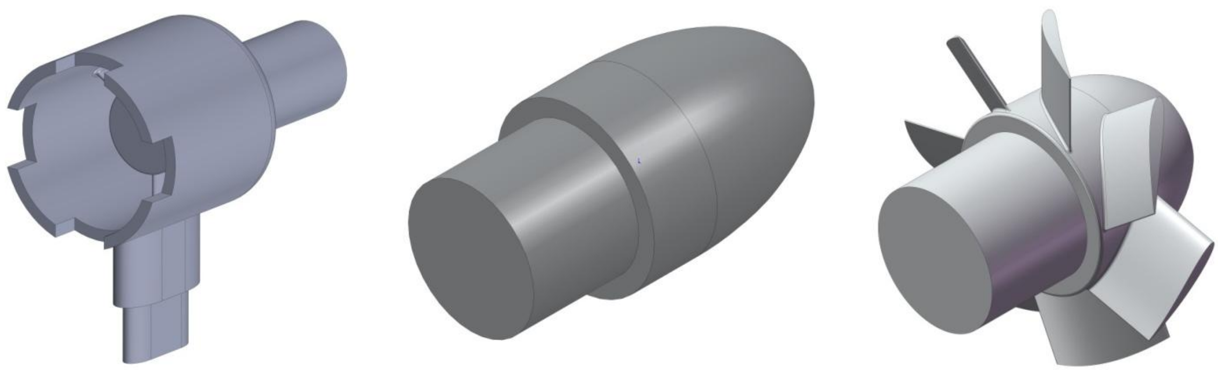


Figure 17. Cowling, tip, and blisk with gates for casting.

The models were built in the Objet rapid prototype machine. This machine was chosen because it has a higher resolution in the z-axis (vertical) than other machines at Cal Poly.

Wax gates were made to attach the parts to. First wax was poured into wood molds and then a CNC mill was used to cut them down to size. This process is show in Figure 18 and Figure 19. Not all of the gating on the parts fit into the wax gates, so rubber gates were used for these parts.

Figure 18. Wax gates in the wood molds.

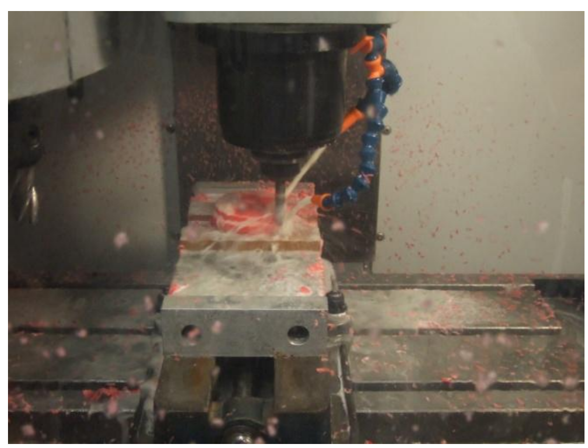


Figure 19. Wax gates being cut on a CNC mill.

After all the gates were done, the rapid prototype parts were attached to the gates with wax. Any cracks between the gate and the rapid prototype part were also sealed with wax to prevent plaster from getting into the wrong parts. For the cowling, a special intermediate piece was used between the rapid prototype part and the wax gate (Figure 20). It was designed by Martin Koch and allows the metal to flow in through the cowling and the strut. This helps the metal to fill the whole mold which prevents voids.

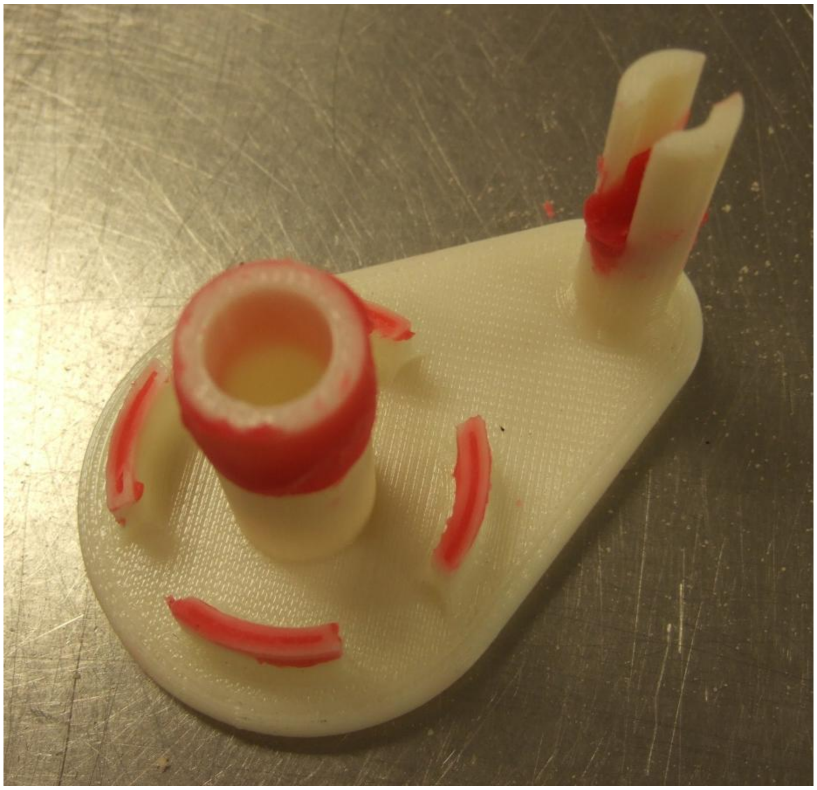


Figure 20. Intermediate piece with wax (red) applied on the surfaces that will mate with the cowling.

Figure 21. The wax gate attached to the rubber base (upside down) with hot glue.

Figure 2 … rapid proto … apid … with wax to prevent plaster from getting inside.

The blisk and the nacelle cap were attached with rubber molds instead of the wax molds because the parts did not fit on the wax molds. Wax molds are hard, which is superior to the flexible rubber molds that allow the part to move slightly while the plaster is being poured and drying.

Figure 23. Blisk mounted in the rubber gate.

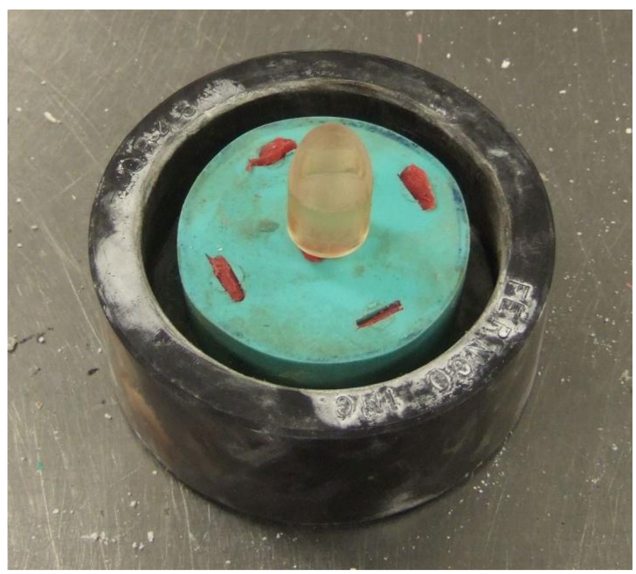


Figure 24. Nacelle cap mounted in the rubber gate.

After all the gating was prepared, the mold container, which is a metal tube, was fit into the rubber base. Plaster of Paris was poured in and vibrated to release any bubbles attached to the part. The molds were slightly overflowed so that after the plaster dried the top could be scraped off, creating a flush top surface.

Figure 25. The mold filled with Plaster of Paris. The machine on the left is a vibrator which was used to shake the mold and release any bubbles before the plaster dried.

After all the molds were poured, the top of the plaster was scraped off when the plaster became firm. The plaster was then allowed to dry and the rapid prototype and wax material was burned out. Unfortunately, both of the molds for the blisk exploded while they were being burned out. This could be due to excessive wax being applied as well as poor temperature control in the oven. One of the molds for the nacelle cap was also damaged. The thin wire way feature broke off at some point during the burn-out process. This was probably because too much wax was used to hold it into the rubber gate, leaving only a little piece of plaster at the bottom which easily broke. The other nacelle cap mold appeared okay, along with both of the cowling molds.

Before the molten aluminum was poured into the molds, the molds were heated up so that they didn't get shocked by the hot metal. The molds were filled with molten aluminum and then put on a shaking table to vibrate out any bubbles. After the metal had cooled, the molds were broken open and the parts cleaned off. The two cowlings and the nacelle cap both came out without any voids.

Figure 26. One of the two casted cowlings and the nacelle cap.

Figure 27. The casted cowling after the plaster was cleaned off. There is a lot of flash around the inside and outside of the cowling.

As show in Figure 27, the nacelle had a lot of flash around the edge of the cowling which needed to be filed off. The nacelle cap did not have any flash, but the wire way, which was supposed to go all the way through, was filled with aluminum.

Figure 28. The nacelle after the flash was filed off.

Figure 29. The wire way on the nacelle cap did not go all the way through like it should.

After the nacelles were cut off of the base, they were put on a lathe to perform the finish machining. The inner diameter of the cowling was bored out to 1.35” using a boring bar. The nacelle needed to be drilled out to 16mm, but the on-campus machine shops did not have the appropriate sized drill or a boring bar of the correct length. Around the same time, the CNC parts were being completed. Because the CNC parts were coming out better looking, as well as fully machined, the casting process was abandoned.

Figure 30. Cast part after the inner surface of the nacelle was bored.

Figure 31. Cast part showing the nacelle drilled out.

Although the casting process was not chosen as the final method of manufacturing, we feel that it was necessary to perform so that we could make a good recommendation on which process was best. From performing the casting, there were several things that we learned. First, the amount of wax used on the blisk should be minimal to prevent the mold from exploding. Also, making the gate on the blisk hollow would have reduced the chance of it exploding. Controlling the temperature in the oven is also important, as well as eliminating any temperature gradients.

Chapter 6: Design Verification

To verify that our team's device would meet the power requirement specified in Table 1, we tested our device in the wind tunnel at Cal Poly. The wind tunnel at Cal Poly can reach a maximum speed of approximately 160 ft/s, which is not flight speed, but the data can be used to predict the power output at different conditions.

The main purpose for the first experiment was to familiarize ourselves with operation of a wind tunnel and its related equipment as well as fully understand the concepts behind using a brushless DC motor as a generator. We also wanted to test the feasibility of using the three phase power directly without a rectifier. Neither of the metal models were finished at that time so rapid prototyped parts of the same geometries were used in place of the finished parts. Our team believed this to be acceptable because it was a preliminary test to iron out testing procedure. Figure 32 shows the testing set up for the first test.

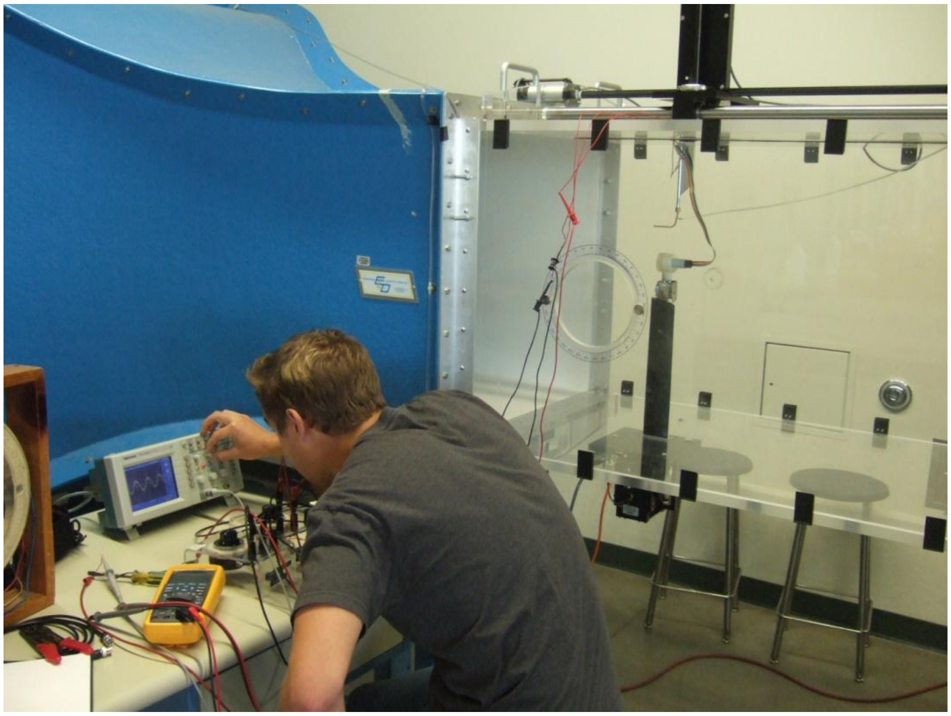


Figure 32. Initial wind tunnel test set up using the "delta" configuration.

This experiment was conducted by wiring the generator to three variable resistors of approximately equal resistance in a "delta" configuration (see figure 33) and measuring the peak to peak voltage across one of the resistors.

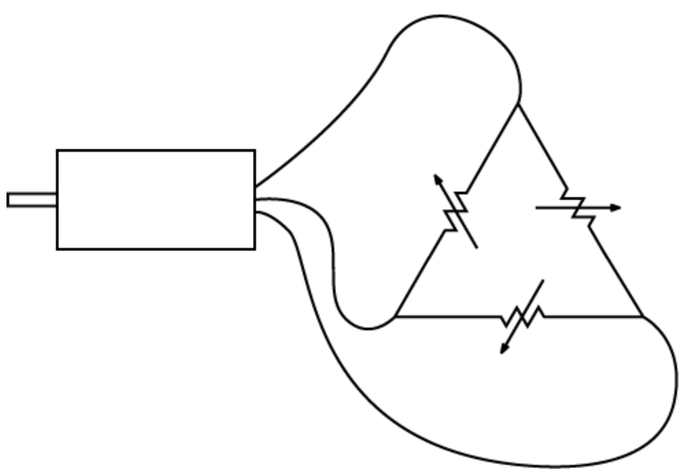


Figure 33. Wiring diagram for the delta confirguation.

We assumed that the voltage across each resistor was the same due to symmetry of the circuit, and since the resistance was known, we calculated the power output with the following equation:

$$P = 3\frac{(V_{RMS})^2}{R}$$

First we set all three resistors to the same resistance using a multimeter. Next we measured the voltage across one of the resistors at various wind speeds. Power output was calculated using the above equation, which produced the graphs in Figure 34 and Figure 35. We also measured the frequency of the voltage sine wave, which told us the rotational speed of the motor.

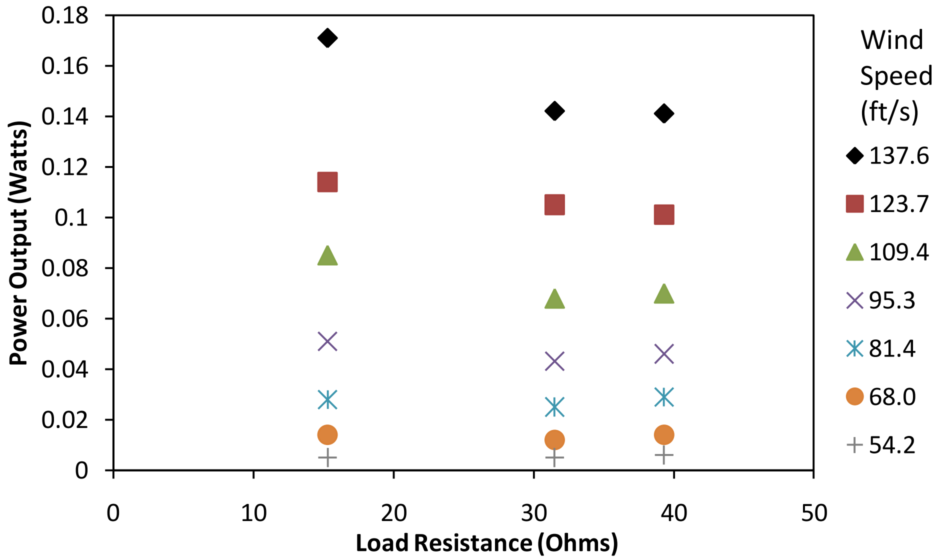


Figure 34. Test data at 137.6 ft/s. The power generated is much less than we expected. It is probably because the resistances tested were way above the ideal range.

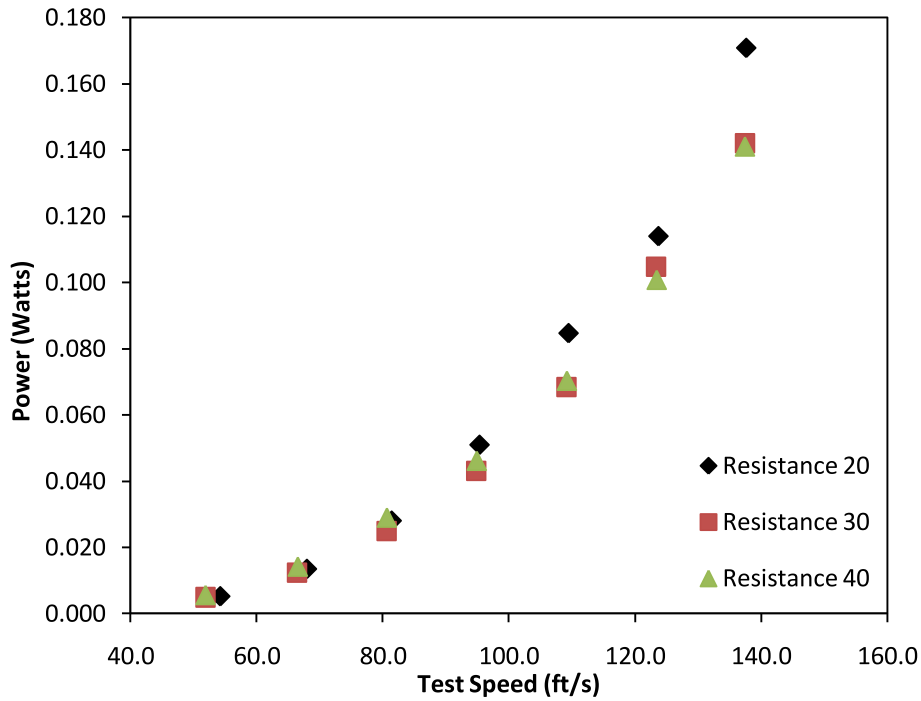


Figure 35. Test data correlating power output to wind speed at various resistances.

Wind speed was measured by taking pitot-static pressure measurements and converting them to a linear wind speed. The raw data for this test can be found in the Appendix I.

We found that power output was higher for a lower resistance than higher values. We also found that in order to predict power output at higher wind speeds, more data points between resistances need to be gathered. The hardest part about this procedure was setting the potentiometers to the same resistance because the multimeter had trouble getting an accurate resistance reading and kept jumping around. Also, each potentiometer had to be removed from the circuit in order to set the resistance. This added a lot of extra time to the testing procedure.

In our next test we used rapid prototype parts again, but this time we decided to test power output using a rectifier. The rectifier converts three phase AC power to DC power. This makes the testing easier because we can just measure voltage and current while varying the resistance, which can be calculated later using Ohms law. Since there is only one potentiometer, it eliminates the extra step of measuring each potentiometer and setting them equal. The raw test data can be found in the Appendix I. Figure 36 shows the results from this test. At the max wind speed, power peaked at 9.7 Watts.

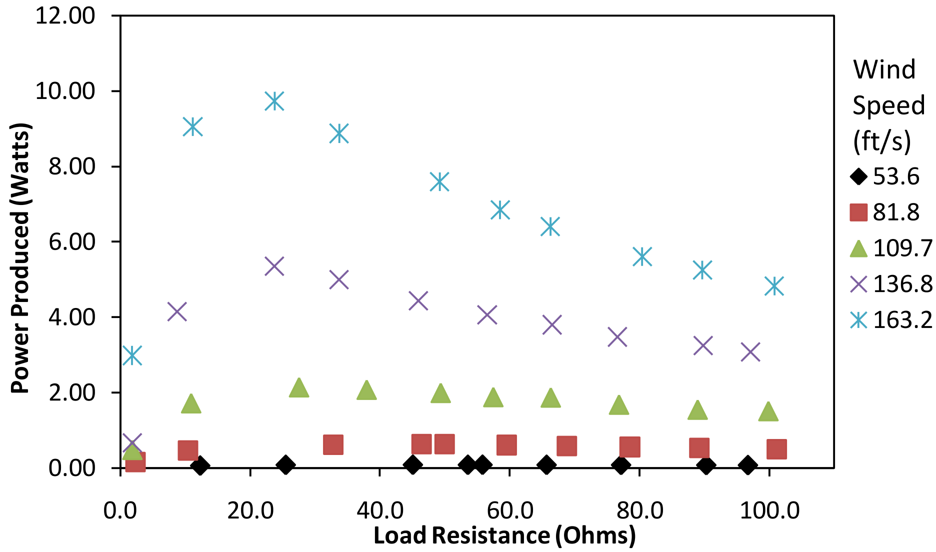


Figure 36. Test data from our second wind tunnel test with the rectifier and rapid prototype parts. At the max wind speed of 163.2 ft/s, the peak power created was 9.7 Watts for a load resistance of 23.8 Ohms.

This test was successful in showing that our design can produce a similar amount of power to the previous group, who produced a max power of approximately 10 Watts in the same wind tunnel. Because testing with the rectifier is so much quicker than without, we decided that we would continue testing with the rectifier instead of using the three phase power directly.

For our third test we had completed the CNC model. The CNC model used the 13mm motor instead of the 16mm motor that the rapid prototype models used (see Chapter 4 for more information on the two motors). This had some unexpected consequences that are discussed later. Figure 37 displays the final testing set up used to find the power output.

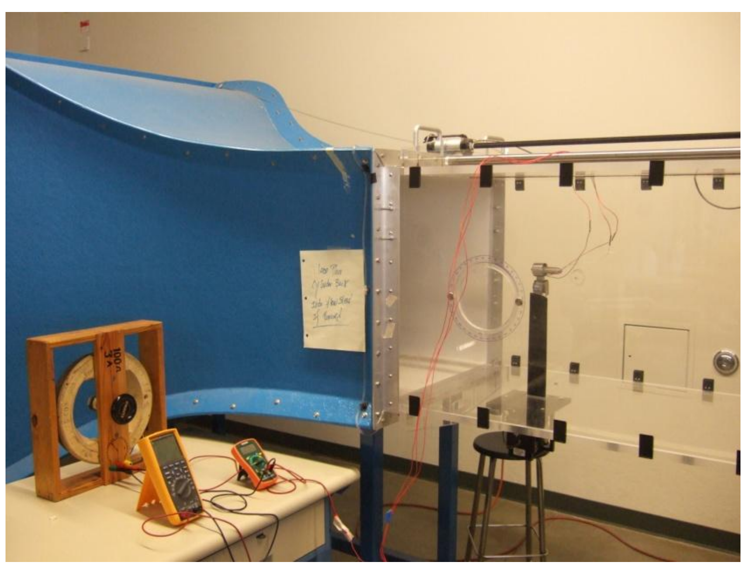


Figure 37. Final test set up with rectified voltage.

This test followed the same procedure as the previous test. The motor was connected to a rectifier, and the DC output from the rectifier was connected to a large potentiometer. The voltage and current for the potentiometer were measured as the resistance was varied. This was repeated for several wind speeds, giving us a good array a data at different conditions. The data from this test is shown in Figure 38.

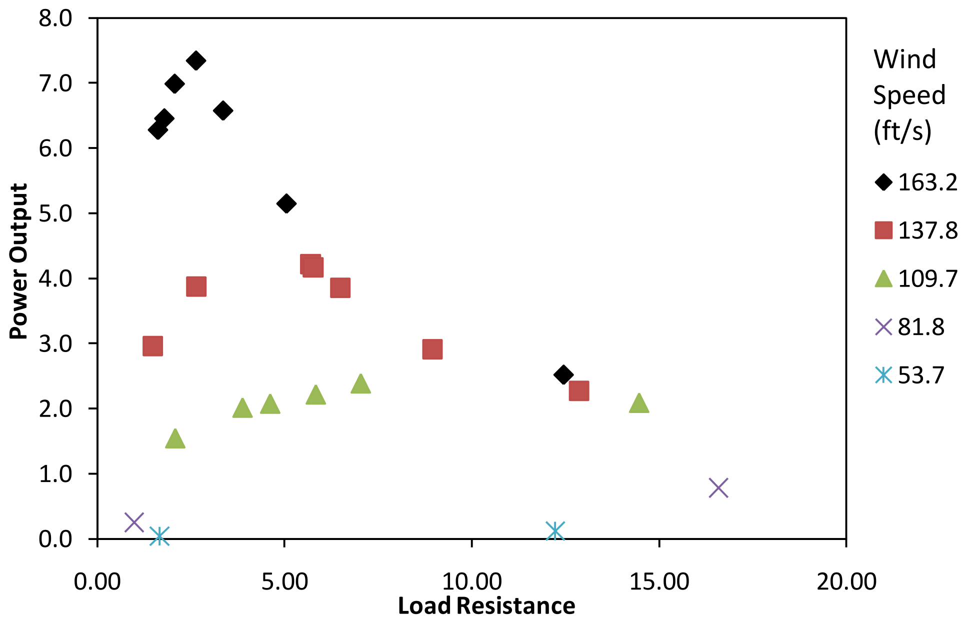


Figure 38. Test data using the CNC model and the 13mm motor. At the top wind speed of 163.2 ft/s, 7.3 Watts was produced at a load resistance of 2.3 ohms.

The first thing we noticed is that this test produced less power than the previous test for an equivalent wind speed. This is most likely due to a design flaw in our device. Because the 13mm motor has preloaded ball bearings, the shaft can be pushed inwards about 3mm. Since the blisk is mounted directly on the shaft, at higher wind speeds it gets pushed in and the back of the blisk rubs on the cowling, as seen in Figure 39. We attempted to space the blisk away from the cowling to prevent them from coming into contact at higher wind speeds, but the short shaft on the motor did not allow us to space it away enough.

Figure 39. The cowling showing marks from the blisk rubbing on it.

The other difference between the results from this test and those from the last test is the resistance which produces peak power. In the previous test it was around 23 Ohms, in this test it is one-tenth of that at 2.3 ohms. This is probably due to the physical properties of the smaller motor. The resistance between two wires for the 13mm motor is lower than that for the 16mm motor which causes the ideal load resistance to be lower also.

To predict power produced at flight conditions, we used the following equation:

$$P_{flight} = P_{test} * \frac{\rho_{flight} * V_{flight}^3}{\rho_{test} * V_{test}^3}$$

Although the flight speed is higher than our testing wind speed, the air density is much lower because of the high altitudes. Power output for various flight conditions are show Figure 40.

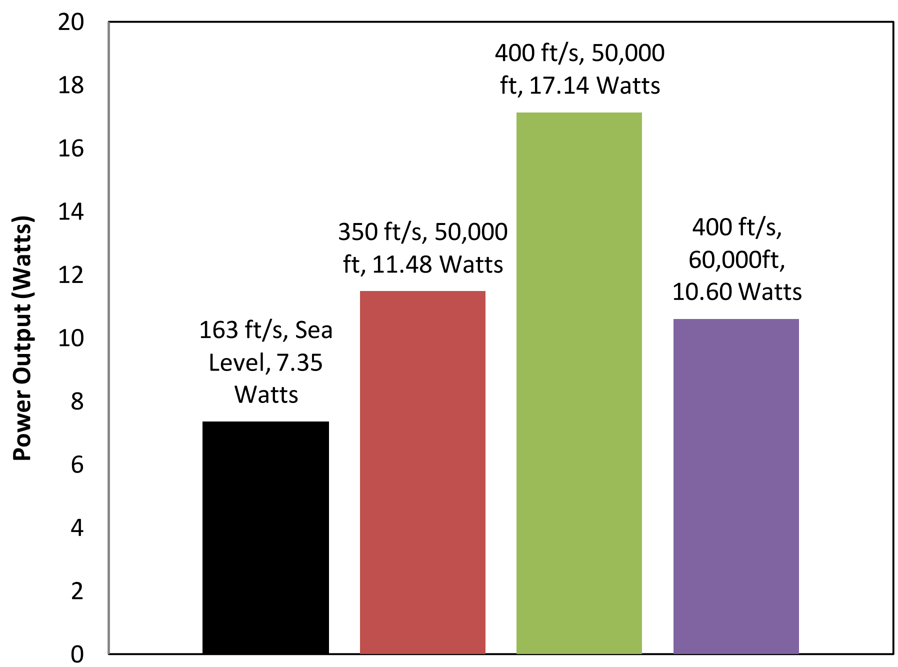


Figure 40. Power output for flight at various speeds and altitudes.

Our tests clearly show that our device is capable of producing power. Although we did not meet our goal of 50 Watts, we do not feel like it was a failure. This was a very broad estimate based on one specific flight condition. At different flight conditions (specifically, lower altitudes), the power required to heat the BLDS will be less. Additionally, another estimate says that the temperature of the BLDS will increase approximately 1°C per Watt. Based on this prediction, our device would produce enough power to heat the sensors to operating temperature.

Chapter 7: Conclusions and Recommendations

Testing of the current prototype did show that the micro ram air turbine can provide power in flight conditions to heat the BLDS, and that the ram air turbine is a viable solution to provide heating power to devices similar to the BLDS. Due to the fact that power output varies with altitude and air temperature, Team IcePick recommends that the BLDS heater only be used for auxiliary power (as is the case for heating the BLDS) and more testing would have to be conducted in order to determine if it can be the sole power source for test instrumentation. Below is the table introduced in Chapter 2 which outlined the requirements for the BLDS heater:

Table 12. Comparison of prototype to specifications

Parameter Description	Target	Tolerance	Prototype	Verification Method	Pass/Fail
Internal temperature of BLDS	-20 °C	± 20 °C	Unknown	Test	N/A
Operating altitude	50,000 ft	Max	50,000+	Analysis	Pass
Outside air temperature	-60 °C	Max	Unknown	Test	N/A
Max onset velocity	350 ft/s	Max	350+ ft/s	Analysis	Pass
Power output from turbine (at 350 ft/s and 50,000 ft)	50 W	Min	11.48 W	Test/Analysis	Fail
Weight	1 lb	Max	0.3 lb	Test	Pass

While Team IcePick failed on power output of the BLDS heater, this does not mean the device would fail to heat the BLDS. Team IcePick had a projected power output of 11.48 Watts at flight conditions which was a result of testing and analysis. The method of analysis used to predict the power output at flight conditions assumes that the blisk power input into the generator will scale linearly with density and cubically with windspeed. This is not an actual value which will occur at flight conditions; furthermore, the rubbing condition between the blisk and cowling described Chapter 5 could be preventing the generator from producing as much power as it should be at higher wind speeds. If this condition were fixed we are confident that better power output results could be obtained. Team IcePick is still confident that the BLDS heater will be able to provide an ample amount of heating power to the BLDS and that this additional heating power should help broaden the range of flight conditions which the BLDS operates.

Team IcePick was pleased to have a functioning prototype, however we do suggest a second generation prototype be made. As mentioned in Chapter 5, the machined model could function a lot better if it had the same generator which was selected for the cast model. This generator features a longer shaft and it does not have preloaded ball bearings which eliminates the blisk/cowling rub problem. In order to accommodate the larger diameter generator, modifications would have to be made to the cowling and nacelle, but Team IcePick feels like these modifications would benefit the entire device significantly by possibly providing a higher power output and increasing the simplicity of assembly.

While Team IcePick failed to complete a prototype which was cast, this was mainly a result of the resources available to Team IcePick. Cal Poly's casting lab is relatively primitive compared to current processes and Team IcePick still deems casting as the favored method of manufacture for the blisk and nacelle due to the multiple set ups and special tooling required to machine them.

Before the micro ram air turbine can be flight tested a heater needs to be purchased and also a temperature controller should be considered for purchasing as well. The strip heater will need to have the same resistance which gave Team IcePick's micro RAT the maximum power output. Team IcePick did not consider the purchasing of a strip heater or a controller because of their availability and the fact that we found it wasteful to purchase a heater or controller for a prototype which may not be used for actual flight.

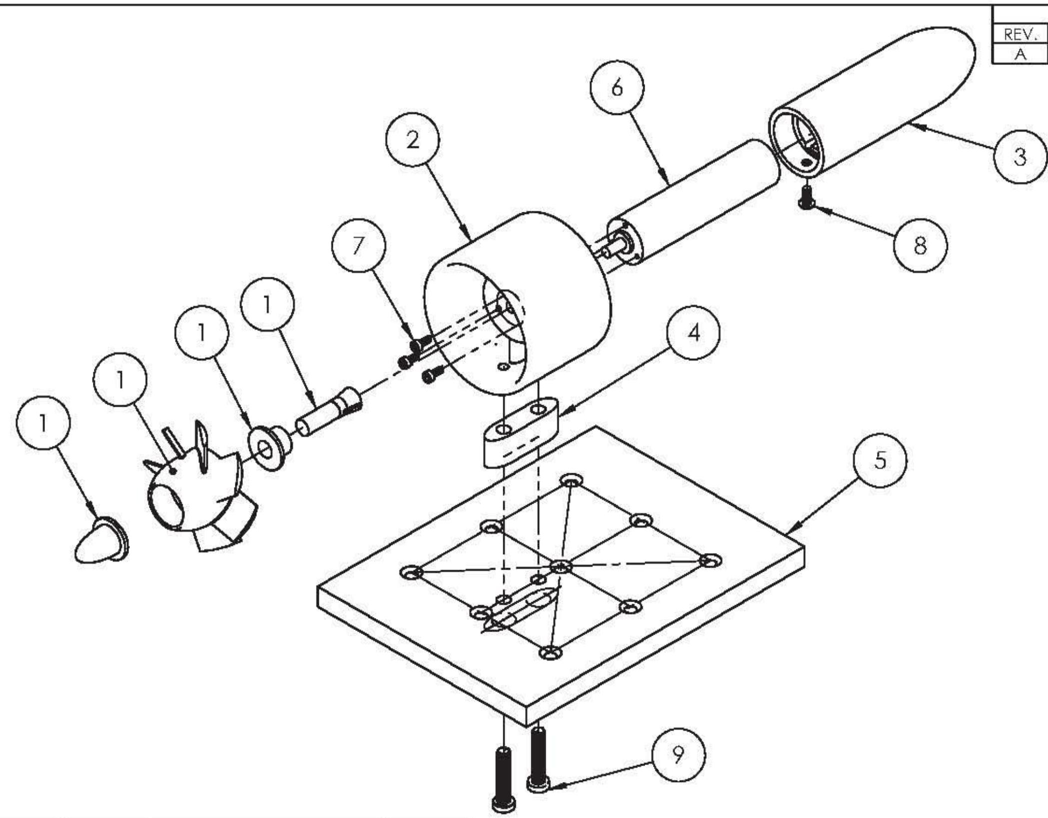
Appendix A. QFD Table

Legend:
9 = Strong Correlation
3 = Marginal Correlation
1 = Minimal Correlation

					Technical Requirements							Planning Matrix	
			Professor Westphal	Pilot	Weight	Power Output	Internal Temperature of BLDS	Outside Air Temperature	Max Onset Velocity	Component Drag Force	Total Lifetime	Original Product	Overall Weighting
Customer Requirements	Functional Performance	Lightweight	5	2	9								
		Maintain heating of BLDS device	5	1		9	9						
		Operates at Standard Flight Conditions	5	1				9	9				
		Product Life	5	1				1			9		
	Human Factors	Manufacturability	3	1									
		Mount in multiple configurations	3	1	3								
		Easy to mount	3	1									
		Attaches with customer adhesive	3	1	1								
		Low maintenance	4	1							9		
	Plane Factors	Does not damage plane	5	5									
		Does not affects flight of plane	2	5	1					3			
		Aircraft grade materials	5	1	1								
		Cost	3	1									
		Design Targets			<1 lb	50 W	-20°C	-60°C	350 ft/s	TBD	TBD		

Appendix B. Final Drawings

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	INTITIAL RELEASE	3/7/2011	RV



ITEM #	PART #	DESCRIPTION	QTY.
1	1001	BLISK ASSEMBLY	1
2	1002	COWLING	1
3	1003	NUCELLE	1
4	1004	SUPPORT STRUT	1
5	1005	MOUNTING PLATE	1
6	1006	GENERATOR	1
7	1007	91290A021	3
8	1008	91255A076	1
9	1009	92220A144	2

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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

Linear Tolerances:
X ±
XX ±
XXX ±
XXXX ±

Angular Tolerances:
X ±
XX ±
XXX ±

MATERIAL Aluminum 6061

FINISH XXXXXXX

DO NOT SCALE DRAWING

	NAME	DATE
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CHECKED		

COMMENTS:

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ICEPICK

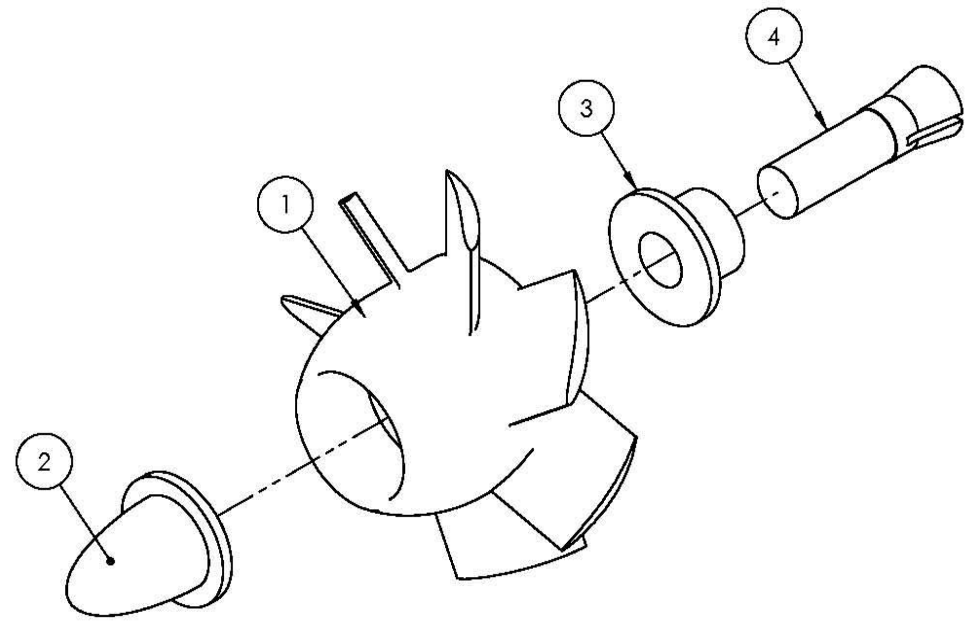
TITLE:
ASSEMBLY,
BLDS HEATING DEVICE

SIZE A | DWG. NO. 1000 | REV A

SCALE: 2:3 | WEIGHT: | SHEET 1 OF 1

4 3 2 1

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	INTIIAL RELEASE	3/7/2011	RV



ITEM #	PART #	DESCRIPTION	QTY.
1	1001A	BLISK	1
2	1001B	COLLETHEAD	1
3	1001C	COLLET COLLAR	1
4	1001D	COLLET BODY	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

Linear Tolerances:	Angular Tolerances:
x. ±	x. ±
x.x ±	x.x ±
x.xx ±	x.xx ±
x.xxx ±	

MATERIAL
Aluminum 6061

FINISH
XXXXXXX

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		

COMMENTS:

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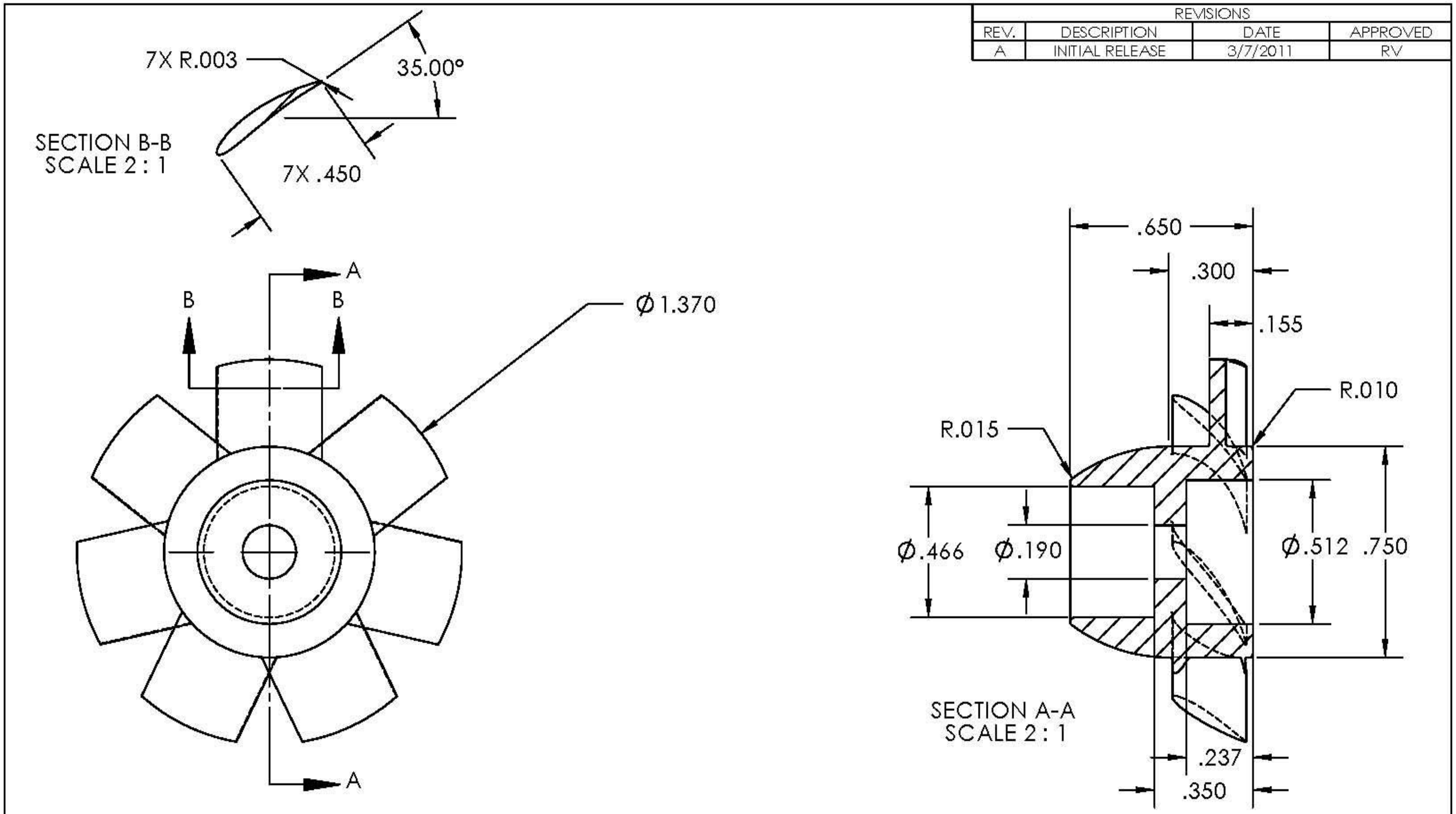
ICEPICK

TITLE:
ASSEMBLY,
BLISK

SIZE	DWG. NO.	REV
A	1001	A
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	INITIAL RELEASE	3/7/2011	RV



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES		NAME	DATE	ICEPICK
	DRAWN	J. Hsu	3/7/2011	
Linear Tolerances:	CHECKED			
x.xx ± .01 x.xxx ± .002	COMMENTS:			TITLE: Blisk
MATERIAL Aluminum 6061	PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TEAM ICE PICK. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TEAM ICE PICK IS PROHIBITED. PROPRIETARY AND CONFIDENTIAL			SIZE A · DWG. NO. 1001A · REV A
FINISH None				
DO NOT SCALE DRAWING				SCALE: 2:1 · WEIGHT: · SHEET 1 OF 1

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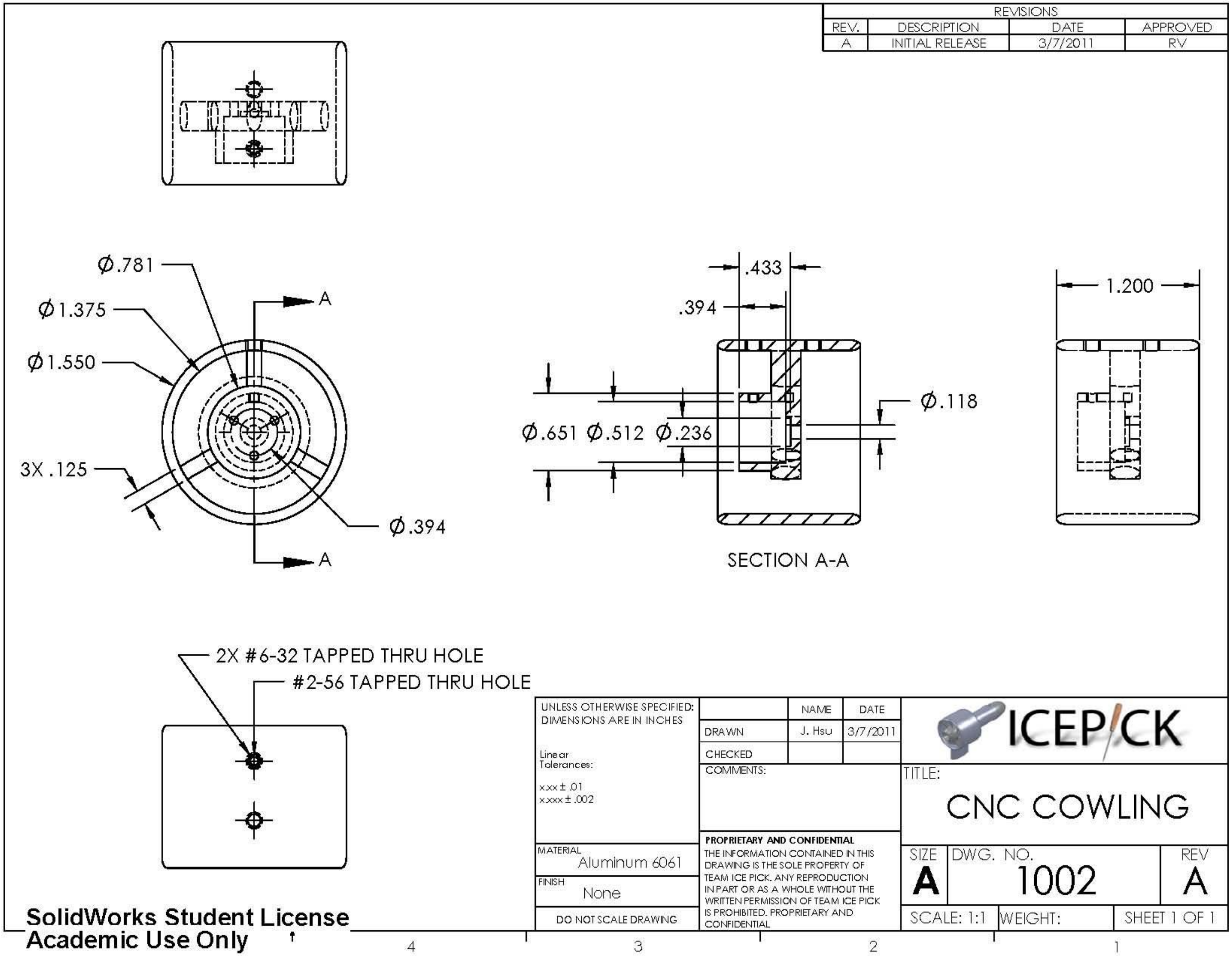
4 3 2 1


REVISIONS
REV. DESCRIPTION DATE APPROVED
A INITIAL RELEASE 3/7/2011 RV
Ø.781
Ø1.375
Ø1.550
3X .125
Ø.394
A
A
.433
.394
Ø.651 Ø.512 Ø.236
Ø.118
SECTION A-A
1.200
2X #6-32 TAPPED THRU HOLE
#2-56 TAPPED THRU HOLE
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
Linear Tolerances:
x.xx ± .01
x.xxx ± .002
NAME DATE
DRAWN J. Hsu 3/7/2011
CHECKED
COMMENTS:
ICEPICK
TITLE:
CNC COWLING
MATERIAL Aluminum 6061
FINISH None
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
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SIZE A
DWG. NO. 1002
REV A
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
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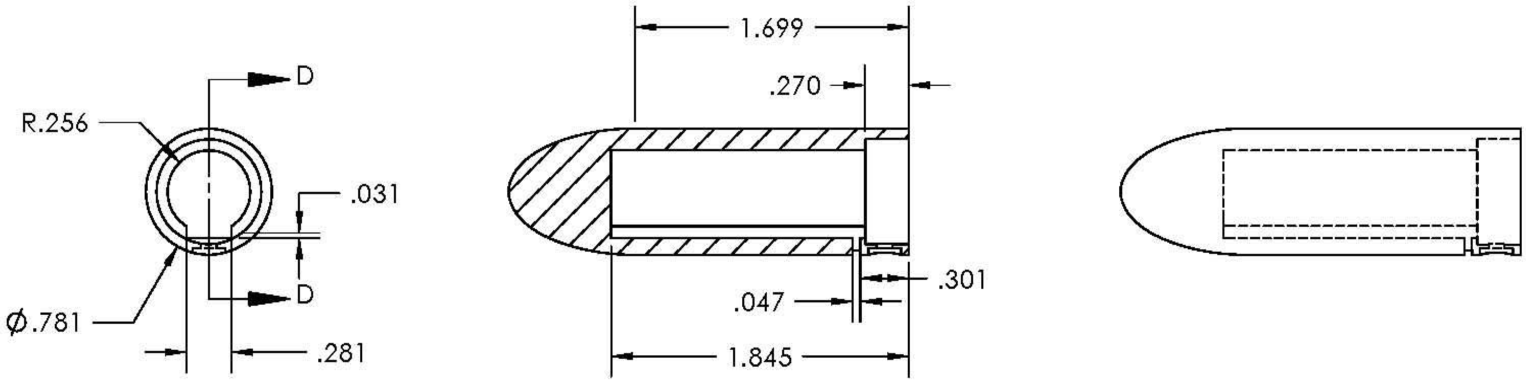
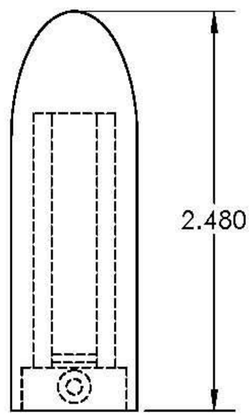
4
3
2
1

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	INITIAL RELEASE	3/7/2011	RV



SECTION D-D
SCALE 1 : 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES		NAME	DATE	ICEPICK
Linear Tolerances: x.xx ± .01 x.xxx ± .002	DRAWN	J. Hsu	3/7/2011	
	CHECKED			TITLE: NUCELLE
	COMMENTS:			
MATERIAL Aluminum 6061	PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TEAM ICE PICK. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TEAM ICE PICK IS PROHIBITED. PROPRIETARY AND CONFIDENTIAL			SIZE A · DWG. NO. 1003 · REV A
FINISH None				
DO NOT SCALE DRAWING				SCALE: 1:2 · WEIGHT: · SHEET 1 OF 1

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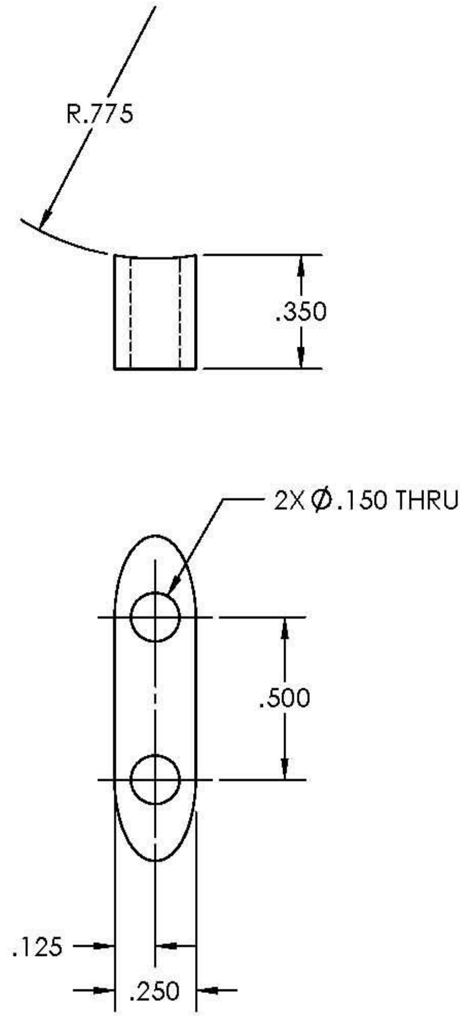
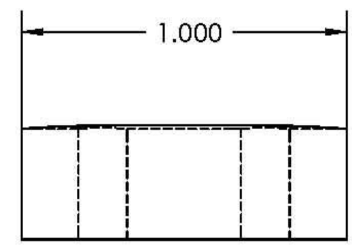
4 3 2 1

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	INITIAL RELEASE	3/7/2011	RV





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES		NAME	DATE
	DRAWN	J. Hsu	3/7/2011
Linear Tolerances: x.xx ± .01 x.xxx ± .002	CHECKED		
	COMMENTS:		
MATERIAL Aluminum 6061			
FINISH None			
DO NOT SCALE DRAWING			

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ICEPICK

TITLE:

SUPPORT STRUT

SIZE	DWG. NO.	REV
A	1004	A
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

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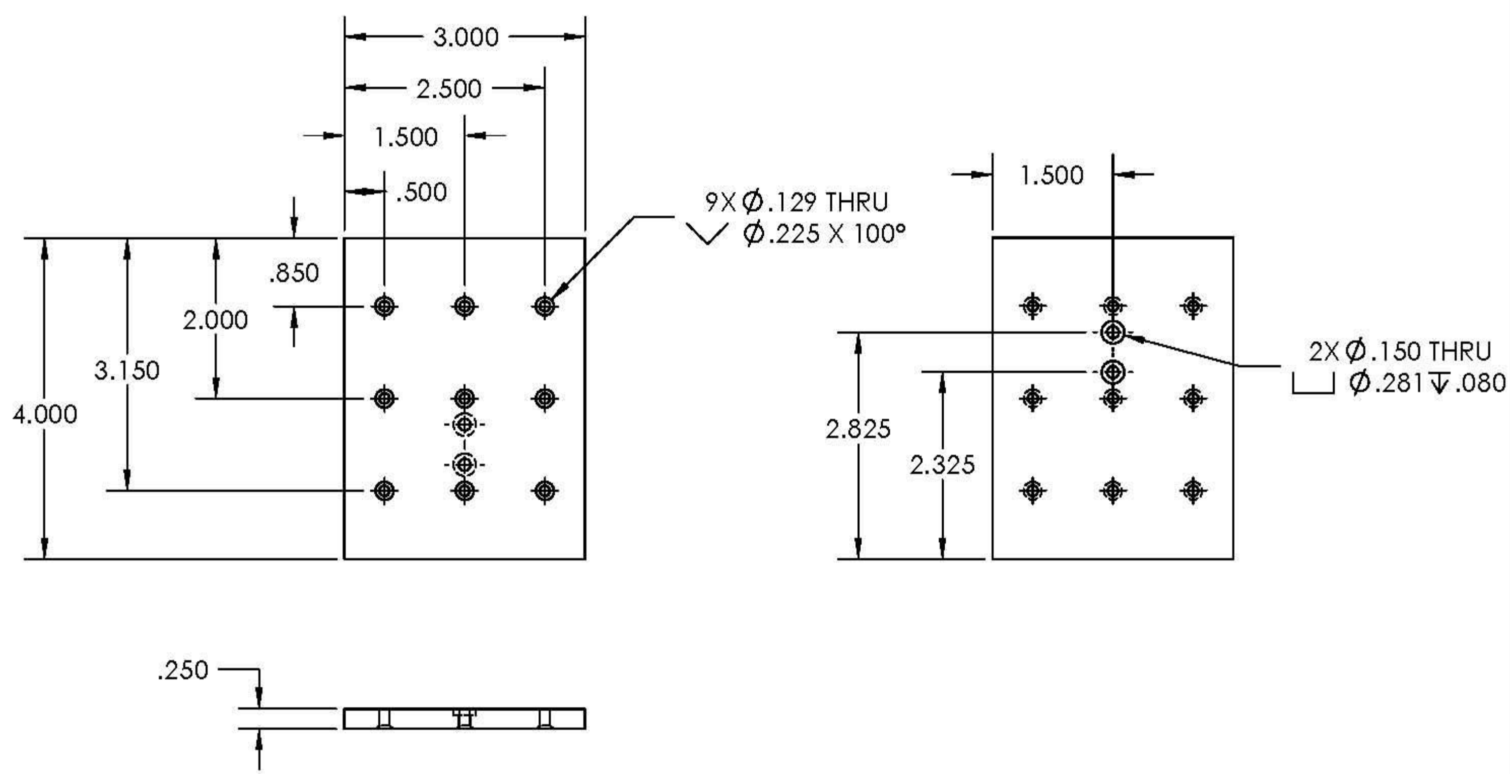
4 3 2 1



REV.	DESCRIPTION	DATE	APPROVED
A	INITIAL RELEASE	3/7/2011	RV

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

Linear Tolerances:
x.xx ± .01
x.xxx ± .002

	NAME	DATE
DRAWN	J. Hsu	3/7/2011
CHECKED		

COMMENTS:

MATERIAL: Aluminum 6061

FINISH: None

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ICEPICK

TITLE: Mounting Plate

SIZE: A | DWG. NO. 1005 | REV: A

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

4 3 2 1

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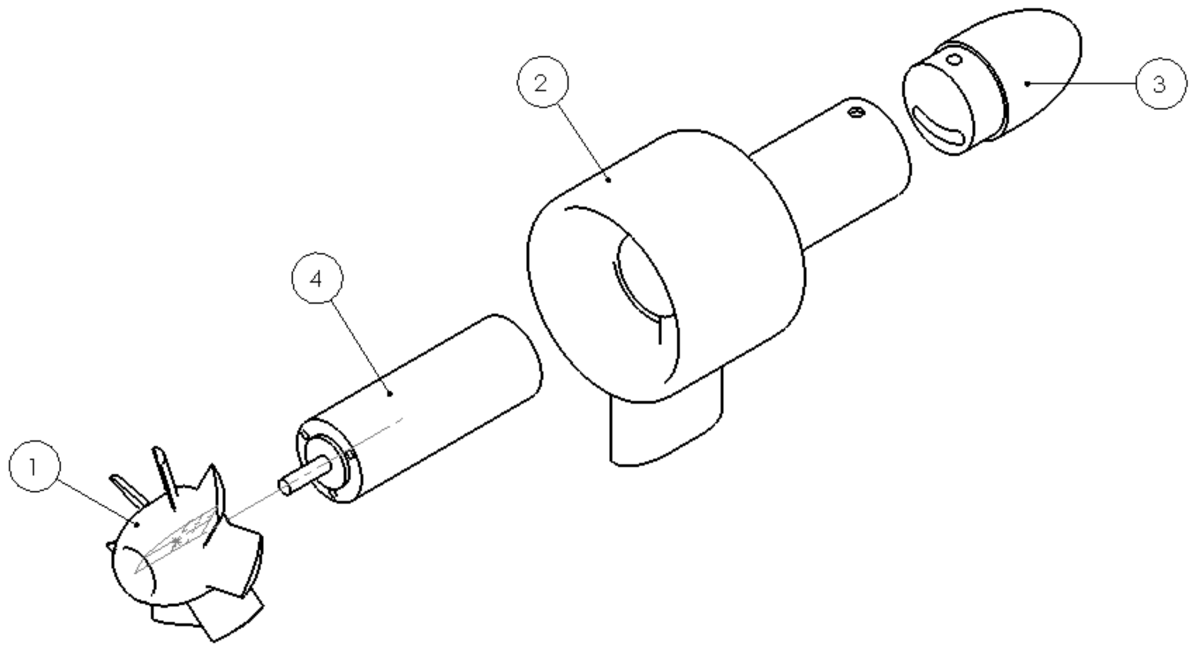
REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	INITIAL RELEASE	3/7/2011	RV



ITEM #	PART #	DESCRIPTION	QTY.
1	1001A	BLISK	1
2	2001	CAST COWLING	1
3	2002	NUCELLE CAP	1
4	2003	GENERATOR 16MM	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

	NAME	DATE
DRAWN		
CHECKED		

Linear Tolerances:
x. ±
xx ±
xxx ±
xxxx ±

Angular Tolerances:
x. ±
xx ±
xxx ±

COMMENTS:

MATERIAL Aluminum 6061

FINISH XXXXXXX

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ICEPICK

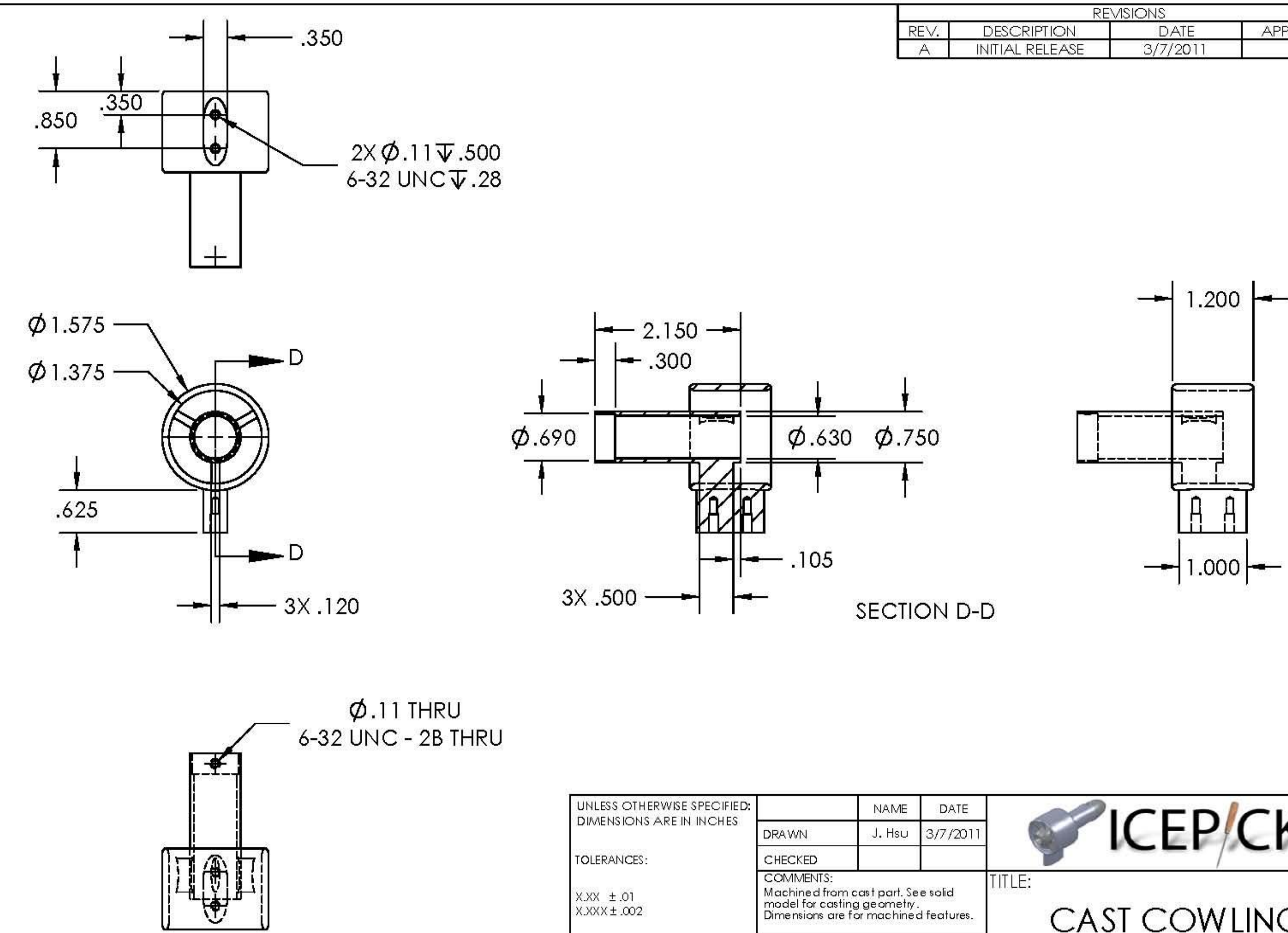
TITLE: ASSEMBLY, CAST MODEL

SIZE A | DWG. NO. 2000 | REV A

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	INITIAL RELEASE	3/7/2011	RV



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES		NAME	DATE
	DRAWN	J. Hsu	3/7/2011
TOLERANCES:	CHECKED		
X.XX ± .01 X.XXX ± .002	COMMENTS: Machined from cast part. See solid model for casting geometry. Dimensions are for machined features.		
MATERIAL Aluminum 356	PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TEAM ICE PICK. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TEAM ICE PICK IS PROHIBITED. PROPRIETARY AND CONFIDENTIAL		
FINISH Cast / Machined			
DO NOT SCALE DRAWING			

ICEPICK

TITLE: CAST COWLING

SIZE	DWG. NO.	REV
A	2001	A
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

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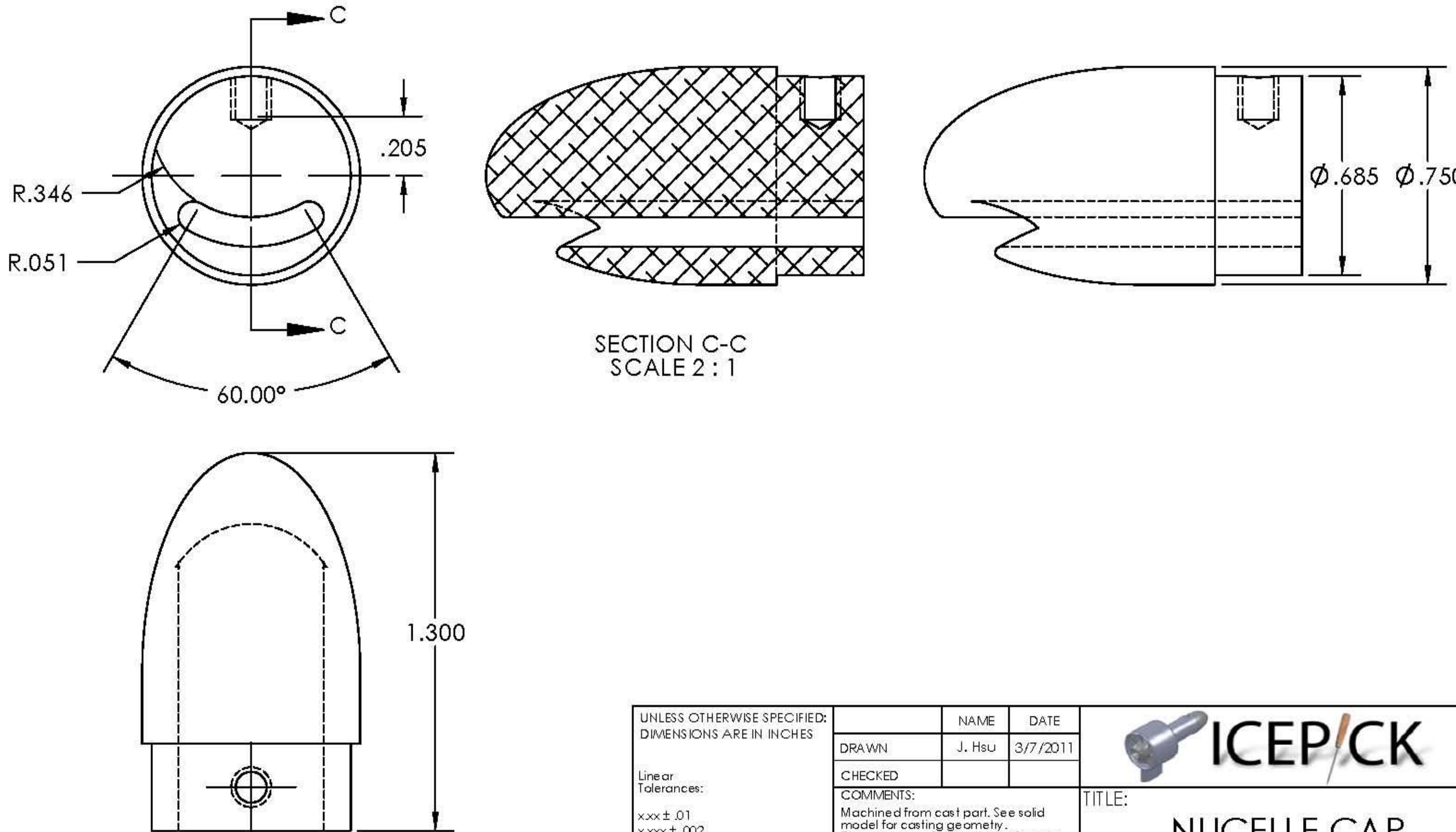
4 3 2 1

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	INITIAL RELEASE	3/7/2011	RV



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES		NAME	DATE
	DRAWN	J. Hsu	3/7/2011
Linear Tolerances: x.xx ± .01 x.xxx ± .002	CHECKED		
	COMMENTS: Machined from cast part. See solid model for casting geometry. Dimensions are for machined features only.		
MATERIAL Aluminum 6061	PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TEAM ICE PICK. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TEAM ICE PICK IS PROHIBITED. PROPRIETARY AND CONFIDENTIAL		
FINISH None			
DO NOT SCALE DRAWING			

ICEPICK

TITLE: NUCELLE CAP

SIZE	DWG. NO.	REV
A	2002	A

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

4 3 2 1

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Appendix C: Vendors

Maxon Motors:

Jeff Randall (Sales Engineer)
Phone: 650-524-8822 Ext. 216
Fax: 650-372-9395
Email: jrandall@maxonmotorusa.com

Shirl Simonson (Inside Sales Coordinator)
Phone: 800-865-7540 Ext. 238
Fax: 650-372-9395
Email: ssimonson@maxonmotorusa.com

Cast Model:

Martin Koch
Phone: 805-756-1114
Fax: 805-756-5439
Email: mkoch@calpoly.edu

Larry Coolidge
Phone: 805-756-1260
Fax: 805-756-5460
Email: lcoolidg@calpoly.edu

CNC Model:

Eric Pulse
Phone: 805-756-5634
Fax: 805-756-1137
Email: epulse@calpoly.edu

McMaster-Carr:

Phone: (630) 833-0300 (Sales)
(630) 600-3600 (Customer Service)
Fax: (630) 834-9427
Web: www.mcmaster.com

Digi-Key:

Phone: 1-800-344-4539
Fax: 218-681-3380
Web: www.digikey.com

Bill of Materials for BLDS Heating Device

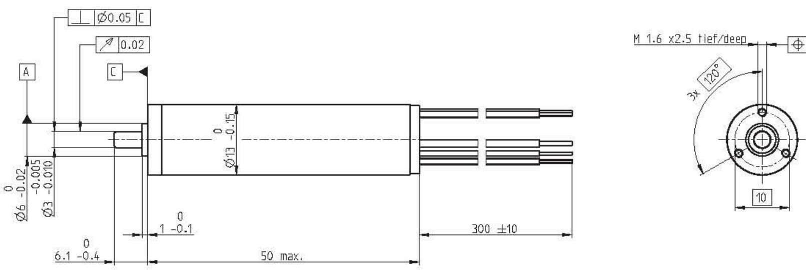
Part	Qty	Description	Source	Part Number	Cost
Aluminum Stock	1	1"x12" 6061 Aluminum Rod	McMaster-Carr	9062K211	$14.40
	1	2"x12" 6061 Aluminum Rod	McMaster-Carr	8974K711	$19.17
	1	2"x2"x12" 6061 Aluminum Bar	McMaster-Carr	9008K531	$31.72
	1	6061 Aluminum Plate needed to manufacture mounting plate/ support strut	McMaster-Carr	9246K13	$19.00
Bolts and Screws	2	M1.6x4 set screw for joining blisk to generator shaft	McMaster-Carr	91390A088	$5.92
	1	Mounting bolts for joining cowling to generator. Package of 25.	McMaster-Carr	91290A021	$4.22
	1	Button cap screw for joining nacelle to cowling. Package of 25.	McMaster-Carr	91255A076	$3.65
	1	Low-profile socket cap screw for joining cowling, strut, mounting plate. Package of 25.	McMaster-Carr	92220A144	$8.92
	1	Collet	N/A	N/A	$3.99
Casting Model	8	Rapid prototype models ($50 per model)	Cal Poly Mechanical Engineering Department	N/A	$400.00
Coding	30	CNC coding for blisk ($20 per hour)	Cal Poly Mechanical Engineering Department	N/A	$600.00
	10	CNC coding for cowling ($20 per hour)	Cal Poly Mechanical Engineering Department	N/A	$200.00
	5	CNC coding for nacelle ($20 per hour)	Cal Poly Mechanical Engineering Department	N/A	$100.00
Generator	1	EC 13 Ø13 mm, brushless, 50 Watt, sterilisable, with Hall sensors	Maxon Motors	384184	$637.85
	1	EC 16 Ø16 mm, brushless, 40 Watt, with Hall sensors	Maxon Motors	232241	$268.94
Machining	35	CNC time for blisk ($20 per hour)	Cal Poly Mechanical Engineering Department	N/A	$700.00
	15	CNC time for cowling ($20 per hour)	Cal Poly Mechanical Engineering Department	N/A	$300.00
	5	CNC time for nacelle ($20 per hour)	Cal Poly Mechanical Engineering Department	N/A	$100.00
Rectifier	1	Rectifier bridge 3 phase	Digi-Key Corporation	FUO22-12N-ND	$9.73
Tooling	4	1/16" Ball End Mill, Carbide, TiN coating	McMaster-Carr	8795A821	$60.20
	2	1/16" Square End Mill, Carbide, TiN coating	McMaster-Carr	4557A121	$34.28
	2	1/8" Square End Mill, Carbide, TiN coating	McMaster-Carr	8770A191	$30.86
	1	1/4" Square End Mill, Carbide, TiN coating	McMaster-Carr	8770A321	$20.20
	1	1/4" Ball End Mill, Carbide, TiN coating	McMaster-Carr	8770A871	$24.35
	2	1/8" Ball End Mill, Carbide, TiN coating	McMaster-Carr	8770A851	$27.16
Total					**$3,624.56**

Appendix D: Component Specifications and Data Sheets

EC 13 Ø13 mm, brushless, 50 Watt, sterilizable

NEW

maxon EC motor



M 1:1

Stock program
Standard program
Special program (on request)

Order Number		1	2	3
A with Hall sensors		384183	384184	384185
B sensorless		384215	384216	384217
Motor Data				
Values at nominal voltage				
1 Nominal voltage	V	12.0	24.0	48.0
2 No load speed	rpm	79300	79400	79400
3 Nominal speed	mA	257	129	64.3
4 Nominal speed	rpm	73600	74100	74200
5 Nominal torque (max. continuous torque)	mNm	7.05	7.94	8.14
6 Nominal current (max. continuous current)	A	5.09	2.85	1.46
7 Stall torque	mNm	113	142	149
8 Starting current	A	78.5	49.5	25.9
9 Max. efficiency	%	89	90	90
Characteristics				
10 Terminal resistance phase to phase	Ω	0.153	0.485	1.85
11 Terminal inductance phase to phase	mH	0.0068	0.0270	0.108
12 Torque constant	mNm / A	1.44	2.88	5.76
13 Speed constant	rpm / V	6630	3320	1660
14 Speed / torque gradient	rpm / mNm	705	559	533
15 Mechanical time constant	ms	2.66	2.11	2.01
16 Rotor inertia	gcm^2	0.360	0.360	0.360

Specifications

Thermal data

17	Thermal resistance housing-ambient	16.0 K / W
18	Thermal resistance winding-housing	0.916 K / W
19	Thermal time constant winding	0.95 s
20	Thermal time constant motor	352 s
21	Ambient temperature	-40 ... +135°C
22	Max. permissible winding temperature	+155°C

Mechanical data (preloaded ball bearings)

23	Max. permissible speed	90000 rpm
24	Axial play at axial load < 2 N	0 mm
	> 2 N	max. 1.2 mm
25	Radial play	preloaded
26	Max. axial load (dynamic)	2 N
27	Max. force for press fits (static)	2 N
28	Max. radial loading, 5 mm from flange	4 N

Other specifications

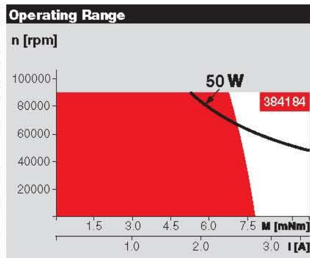
29	Number of pole pairs	1
30	Number of phases	3
31	Weight of motor	44 g

Alignment of the electronic connections not specified.
Values listed in the table are nominal.

Connection A and B, motor (cable AWG 22)
red — Motor winding 1
black — Motor winding 2
white — Motor winding 3
Connection A, sensore (cable AWG 26)
green — V_{Hall} 3.8...24 VDC
blue — GND
red/grey — Hall sensor 1
black/grey — Hall sensor 2
white/grey — Hall sensor 3

Option: Inch-version size 5 available as standard version.

Operating Range



Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

Application

Medicine / surgery / chemicals

Hand tools that can be sterilized, such as bone saw, bone drilling and grinding machine
Dermatological and dental tools
Infusion pumps
ECG
Therapy aid, analysis and dialysis equipment

Sterilization information

In normal use, the motor can be sterilized 500 times in an autoclave. No need to dismantle.

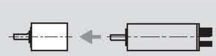
Sterilization with steam

Temperature	+134°C ± 4°C
Compression pressure up to	2.3 bar
Rel. humidity	100 %
Cycle length	20 minutes

maxon Modular System

Overview on page 16 - 21

Planetary Gearhead
sterilizable
Ø13 mm
0.1 - 0.15 Nm
Page 210



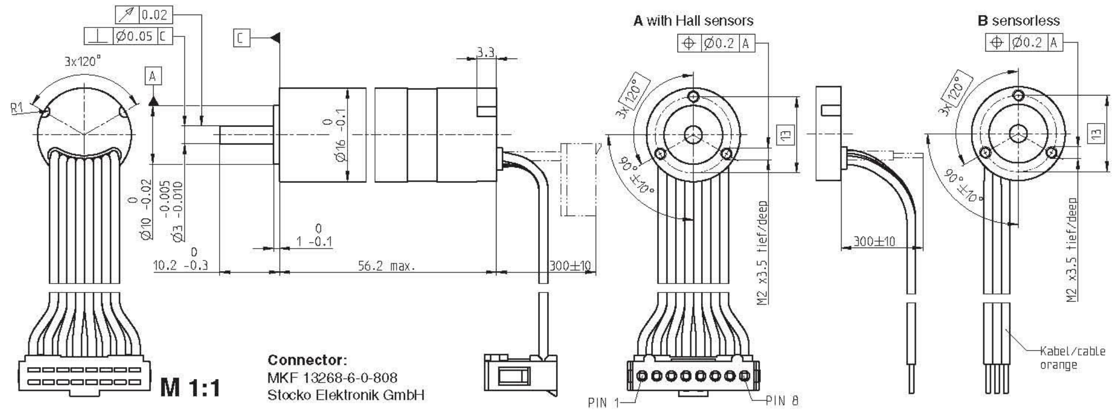
Recommended Electronics:

DECS 50/5, DEC 24/1	p. 289
DEC 24/3	290
DEC Module 24/2	290
DEC 50/5, Module 50/5	291
DECV 50/5	297
Notes	**20**

Choke may be required

May 2010 edition / subject to change

EC 16 ∅16 mm, brushless, 40 Watt



M 1:1

Connector:
MKF 13268-6-0-808
Stocko Elektronik GmbH

- Stock program
- Standard program
- Special program (on request)

Order Number

A with Hall sensors		232242	262860	232241	262862
B sensorless		235689	262864	235686	262866
Motor Data					
Values at nominal voltage					
1 Nominal voltage	V	12.0	18.0	24.0	32.0
2 No load speed	rpm	35800	40300	41400	41400
3 No load current	mA	358	284	222	166
4 Nominal speed	rpm	32100	36700	37900	37900
5 Nominal torque (max. continuous torque)	mNm	13.3	13.4	13.9	13.8
6 Nominal current (max. continuous current)	A	4.51	3.41	2.71	2.03
7 Stall torque	mNm	141	166	184	183
8 Starting current	A	44.5	39.3	33.5	24.9
9 Max. efficiency	%	83	84	85	85
Characteristics					
10 Terminal resistance phase to phase	Ω	0.269	0.458	0.716	1.28
11 Terminal inductance phase to phase	mH	0.0140	0.0249	0.0420	0.0746
12 Torque constant	mNm / A	3.18	4.23	5.50	7.33
13 Speed constant	rpm / V	3010	2260	1740	1300
14 Speed / torque gradient	rpm / mNm	255	244	226	228
15 Mechanical time constant	ms	3.39	3.25	3.01	3.03
16 Rotor inertia	gcm²	1.27	1.27	1.27	1.27

Specifications

Thermal data

17	Thermal resistance housing-ambient	10.3 K / W
18	Thermal resistance winding-housing	1.2 K / W
19	Thermal time constant winding	2.08 s
20	Thermal time constant motor	299 s
21	Ambient temperature	-20 ... +100°C
22	Max. permissible winding temperature	+125°C

Mechanical data (preloaded ball bearings)

23	Max. permissible speed	50000 rpm
24	Axial play at axial load < 3.5 N	0 mm
	> 3.5 N	max.0.14 mm
25	Radial play	preloaded
26	Max. axial load (dynamic)	3 N
27	Max. force for press fits (static)	35 N
	(static, shaft supported)	250 N
28	Max. radial loading, 5 mm from flange	10 N

Other specifications

29	Number of pole pairs	1
30	Number of phases	3
31	Weight of motor	58 g

Values listed in the table are nominal.

Connection A

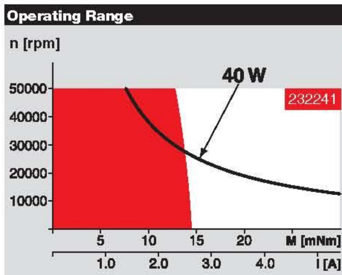
brown	Motor winding 1	Pin 1
red	Motor winding 2	Pin 2
orange	Motor winding 3	Pin 3
yellow	V_{Hall} 4.5 ... 24 VDC	Pin 4
green	GND	Pin 5
blue	Hall sensor 1	Pin 6
violet	Hall sensor 2	Pin 7
grey	Hall sensor 3	Pin 8

Connection B (Cable AWG 24)

brown	Motor winding 1
red	Motor winding 2
orange	Motor winding 3

Wiring diagram for Hall sensors see p. 27

Operating Range



Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

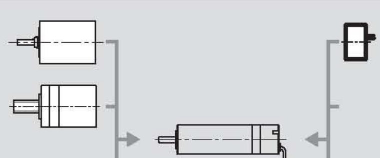
Assigned power rating

maxon Modular System

Overview on page 16 - 21

Planetary Gearhead
∅22 mm
0.5 - 2.0 Nm
Page 224

Spindle Drive
∅22 mm
Page 247 / 248



for type A:
Encoder MR
128 / 256 / 512 Imp.,
Page 261

Recommended Electronics:

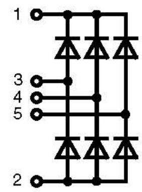
DECS 50/5	Page 289
DEC 24/3	290
DEC 50/5	291
DECV 50/5	297
DES 50/5	298
EPOS2 Module 36/2	304
EPOS 24/1	304
EPOS2 24/5, EPOS2 50/5	305
EPOS P 24/5	308
Notes	**20**

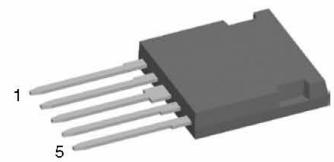
May 2010 edition / subject to change

Three Phase Rectifier Bridge
in ISOPLUS i4-PAC™

I_{dAV} = 28 A
V_{RRM} = 1200/1600 V

V_{RSM} V	V_{RRM} V	Type
1300	1200	FUO 22-12N
1700	1600	FUO 22-16N





Symbol	Conditions			Maximum Ratings	
I_{dAV} ①	T_C = 90°C, rect. 120°			28	A
I_{dAVM} ①	module, rect. 120°			35	A
I_{FSM}	T_{VJ} = 45°C;	t = 10 ms	(50 Hz)	100	A
	V_R = 0	t = 8.3 ms	(60 Hz)	106	A
	$T_{VJ} = T_{VJM}$;	t = 10 ms	(50 Hz)	85	A
	V_R = 0	t = 8.3 ms	(60 Hz)	90	A
I^2t	T_{VJ} = 45°C;	t = 10 ms	(50 Hz)	50	A^2s
	V_R = 0	t = 8.3 ms	(60 Hz)	47	A^2s
	$T_{VJ} = T_{VJM}$;	t = 10 ms	(50 Hz)	36	A^2s
	V_R = 0	t = 8.3 ms	(60 Hz)	33	A^2s
T_{VJ}				-55...+150	°C
T_{VJM}				150	°C
T_{stg}				-55...+125	°C
V_{ISOL}	50/60 Hz, RMS	t = 1 min		2500	V~
	$I_{ISOL} \leq$ 1 mA	t = 1 s		3000	V~
F_C	mounting force with clip			20 ... 120	N
P_{tot}	T_{VJ} = 25°C			30	W
Weight	Typ.			9	g

Symbol	Conditions		Characteristic Values	
I_R	$V_R = V_{RRM}$	T_{VJ} = 25°C	5	µA
		$T_{VJ} = T_{VJM}$	typ. 0.2	mA
V_F	I_F = 15 A	T_{VJ} = 25°C	1.3	V
V_{T0}	for power-loss calculations only		0.8	V
r_t			30	mΩ
R_{thJC}	(per diode)		4	K/W
R_{thCH}			typ. 1	K/W
d_S, d_A	pin - pin		1.7	mm
d_S, d_A	pin - backside metal		5.5	mm
a	Max. allowable acceleration		50	m/s^2
C_P	coupling capacity between shorted pins and mounting tab in the case		typ. 40	pF

Data according to IEC 60747 and refer to a single diode unless otherwise stated.
① for resistive load at bridge output

Features

- rectifier diodes for line frequency
- ISOPLUS i4-PAC™ package
  - isolated back surface
  - UL registered E 72873
  - low coupling capacity between pins and heatsink
  - enlarged creepage towards heatsink
  - application friendly pinout
  - high reliability
  - industry standard outline

Applications

- three phase mains rectifiers

20070627a

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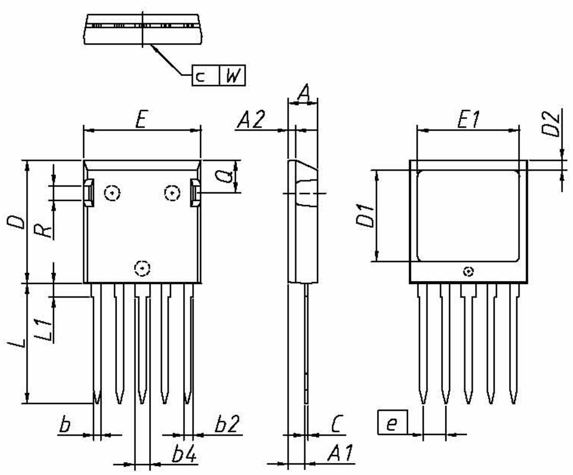
Dimensions in mm (1 mm = 0.0394“)



DIM.	MILLIMETER		INCHES	
	MIN	MAX	MIN	MAX
A	4,83	5,21	0,190	0,205
A1	2,59	3,00	0,102	0,118
A2	1,17	2,16	0,046	0,085
b	1,14	1,40	0,045	0,055
b1	1,47	1,73	0,058	0,068
b2	2,54	2,79	0,100	0,110
C	0,51	0,74	0,020	0,029
D	20,80	21,34	0,819	0,840
D1	14,99	15,75	0,590	0,620
D2	1,65	2,03	0,065	0,080
E	19,56	20,29	0,770	0,799
E1	16,76	17,53	0,660	0,690
e	3,81	BSC	0,15	BSC
L	19,81	21,34	0,780	0,840
L1	2,11	2,59	0,083	0,102
Q	5,33	6,20	0,210	0,244
R	2,54	4,57	0,100	0,180
W	–	0,10	–	0,004

Die konvexe Form des Substrates ist typ. < 0,05 mm über der Kunststoffoberfläche der Bauteilunterseite

The convex bow of substrate is typ. < 0.05 mm over plastic surface level of device bottom side

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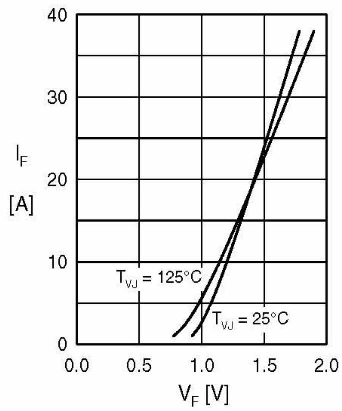

Fig. 1 Forward current vs. voltage drop per diode

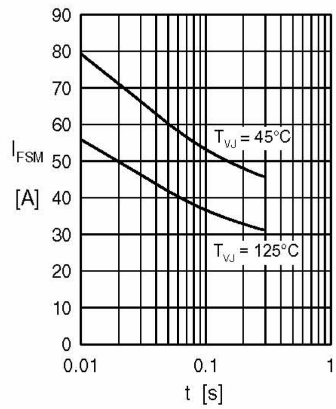

Fig. 2 Surge overload current per diode
I_{FSM}: crest value. t: duration

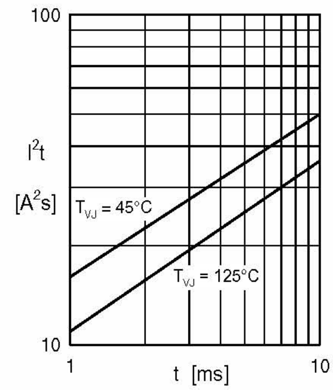

Fig. 2 I^2t versus time (1-10 ms) per diode

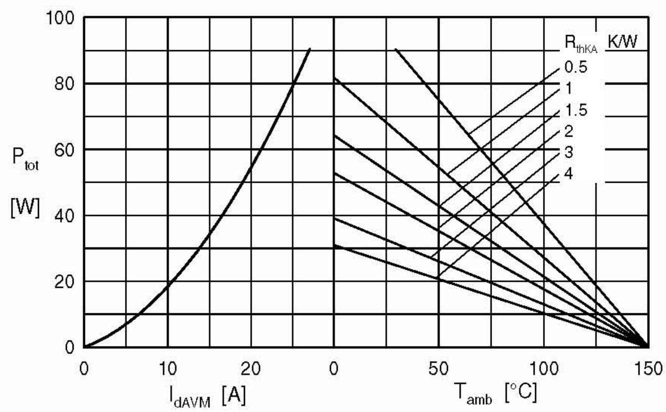

Fig. 3 Power dissipation vs. direct output current and ambient temperature

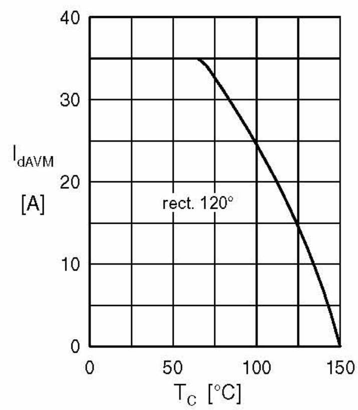

Fig. 4 Maximum forward current at case temperature T_C

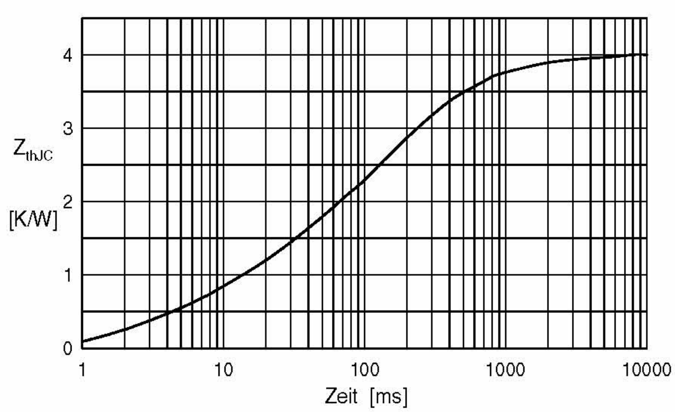

Fig. 5 Transient thermal impedance junction to case per diode

Constants for Z_{thJC} calculation:

i	R_{thi} (K/W)	t_i (s)
1	0.0007604	0.00001
2	0.03587	0.00005
3	0.2439	0.011
4	0.7173	0.067
5	0.5021	0.028

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Aluminum

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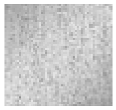

8974K711

[ ] Each

In stock for $21.81

More About Aluminum and Aluminum Alloys

Material	Multipurpose Aluminum (Alloy 6061)
Shape	Rods and Discs
Finish/Coating	Unpolished (Mill)
Tolerance	Standard
Diameter	2"
Diameter Tolerance	±.024"
Length	12"
Length Tolerance	±1"
Straightness Tolerance	Not Rated
Test Report	Without Test Report
Temper	T6511
Hardness	95 Brinell
Yield Strength	35,000 psi
Temperature Range	-320° to +300° F
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM B221
WARNING	Hardness and yield strength are not guaranteed and are intended only as a basis for comparison.

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Aluminum

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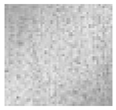
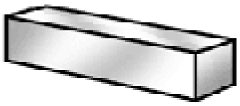


9008K531

[ ] Each

In stock for $36.55



More About Aluminum and Aluminum Alloys

Material	Multipurpose Aluminum (Alloy 6061)
Shape	Sheets, Bars, Strips, and Cubes
Sheets, Bars, Strips, and Cubes Type	Plain
Finish/Coating	Unpolished (Mill)
Edge Type	Square
Tolerance	Standard
Thickness	2"
Thickness Tolerance	±.024"
Length	12"
Length Tolerance	±1"
Width	2"
Width Tolerance	±.024"
Test Report	Without Test Report
Temper	T6511
Hardness	60-95 Brinell
Yield Strength	35,000 psi
Flatness Tolerance	Not Rated
Temperature Range	-320° to +300° F
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM B221
WARNING	Hardness and yield strength are not guaranteed and are intended only as a basis for comparison.

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Aluminum

Catalog Page | Bookmark

9062K211

Each

In stock for $14.40

More About Aluminum and Aluminum Alloys

Material	Multipurpose Aluminum (Alloy 6061)
Shape	Rods and Discs
Finish/Coating	Precision Ground
Tolerance	Tight
Diameter	1"
Diameter Tolerance	-.0005"
Length	12"
Length Tolerance	±1"
Straightness Tolerance	.001" per foot
Test Report	Without Test Report
Temper	T6511
Hardness	Not Rated
Yield Strength	35,000 psi
Temperature Range	-320° to +300° F
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM B221
WARNING	Hardness and yield strength are not guaranteed and are intended only as a basis for comparison.

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Aluminum

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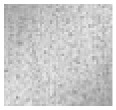
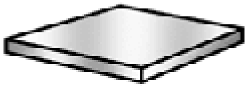


9246K13

Each

In stock for $19.00



More About Aluminum and Aluminum Alloys

Material	Multipurpose Aluminum (Alloy 6061)
Shape	Sheets, Bars, Strips, and Cubes
Sheets, Bars, Strips, and Cubes Type	Plain
Finish/Coating	Unpolished (Mill)
Edge Type	Square
Tolerance	Standard
Thickness	1/4"
Thickness Tolerance	±.008"
Length	12"
Length Tolerance	±1/16"
Width	12"
Width Tolerance	±1/16"
Test Report	Without Test Report
Temper	T6511
Hardness	95 Brinell
Yield Strength	35,000 psi
Flatness Tolerance	Not Rated
Temperature Range	-320° to +300° F
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM B221
WARNING	Hardness and yield strength are not guaranteed and are intended only as a basis for comparison.

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Socket Cap Screws

CAD | Catalog Page | Bookmark

91290A021

Packs of 25

In stock for $4.22 per pack

Head Style	Standard
Standard Head Style	Standard
Material Type	Steel
Finish	Black-Oxide
Class	Class 12.9
Drive Style	Hex Socket
Metric Thread Size	M1.6
Metric Thread Pitch	.35 mm
Length	4 mm
Thread Length	Fully Threaded
Thread Direction	Right Handed
Tip Type	Plain
Self-Locking Method	None
Screw Quantity	Individual Screw
Hex Size	1.5 mm
Head Diameter	3 mm
Head Height	1.6 mm
Rockwell Hardness	Minimum C39
Minimum Tensile Strength	174,000 psi
Thread Fit	Class 5g6g
Specifications Met	Deutsche Industrie Normen (DIN), International Organization for Standardization (ISO)
DIN Specification	DIN 912
ISO Specification	ISO 4762

Set Screws

CAD | Catalog Page | Bookmark

91390A088

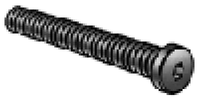
Packs of 1

In stock for $2.96 per pack

Screw Style	Standard Socket
Material Type	Steel
Finish	Black-Finish
Point	Cup
System of Measurement	Metric
Metric Thread Size	M1.6
Metric Thread Pitch	.35 mm
Hex Size	0.7 mm
Length	4 mm
Thread Fit	Class 5g6g
Rockwell Hardness	Minimum C45
Specifications Met	Deutsche Industrie Normen (DIN), International Organization for Standardization (ISO)
ISO Specification	ISO 4029
DIN Specification	DIN 916
Set Screw Quantity	Individual Screw

Socket Cap Screws

CAD | Catalog Page | Bookmark



92220A144

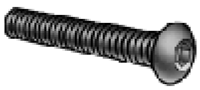
Packs of 25

In stock for $8.92 per pack

Head Style	Low
Material Type	Steel
Finish	Black-Oxide
Class	Not Rated
Drive Style	Hex Socket
Inch Thread Size	6-32
Length	5/8"
Thread Length	Fully Threaded
Thread Direction	Right Handed
Tip Type	Plain
Self-Locking Method	None
Screw Quantity	Individual Screw
Hex Size	1/16"
Head Diameter	.226"
Head Height	.072"
Rockwell Hardness	Minimum C39
Minimum Tensile Strength	145,000 psi
Thread Fit	Class 3A
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM F835

Socket Cap Screws

CAD | Catalog Page | Bookmark



91255A076

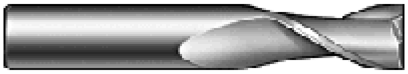
Packs of 25

In stock for $3.65 per pack

Head Style	Button
Material Type	Steel
Finish	Black-Oxide
Class	Not Rated
Drive Style	Hex Socket
Inch Thread Size	2-56
Length	3/16"
Thread Length	Fully Threaded
Thread Direction	Right Handed
Tip Type	Plain
Self-Locking Method	None
Screw Quantity	Individual Screw
Hex Size	.050"
Head Diameter	.164"
Head Height	.046"
Rockwell Hardness	Minimum C39
Minimum Tensile Strength	144,000 psi
Thread Fit	Class 3A
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM F835

End Mills

Catalog Page | Bookmark



4557A121

Each

In stock for $17.14

Type	Square End
Square-End End Mill Type	Tight-Tolerance
End Mill Material	Solid Carbide
Solid Carbide Material Type	Premium Sub-Micrograin
Coating	TiN
Number of Flutes	Two Flute
Single or Double End	Single
End Style	Center Cutting
Mill Diameter	1/16"
Mill Diameter Tolerance	+.001", -.000"
Shank Diameter	1/8"
Length of Cut	3/16"
Overall Length	1-1/2"
Helix Angle	30°
Maximum Working Temperature	+840° F
Color	Gold

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End Mills

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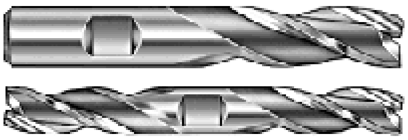

8770A191

Each

In stock for $15.43

Type	Square End
Square-End End Mill Type	General Purpose
End Mill Material	Solid Carbide
Solid Carbide Material Type	Premium Sub-Micrograin
Coating	TiN
Number of Flutes	Three Flute
Single or Double End	Single
End Style	Center Cutting
Mill Diameter	1/8"
Mill Diameter Tolerance	+.000", -.002"
Shank Diameter	1/8"
Length of Cut	3/4"
Overall Length	2"
Helix Angle	30°
Maximum Working Temperature	+840° F
Color	Gold

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End Mills

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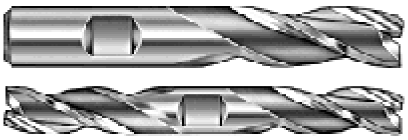

8770A321

Each

In stock for $20.20

Type	Square End
Square-End End Mill Type	General Purpose
End Mill Material	Solid Carbide
Solid Carbide Material Type	Premium Sub-Micrograin
Coating	TiN
Number of Flutes	Three Flute
Single or Double End	Single
End Style	Center Cutting
Mill Diameter	1/4"
Mill Diameter Tolerance	+.000", -.002"
Shank Diameter	1/4"
Length of Cut	3/4"
Overall Length	2-1/2"
Helix Angle	30°
Maximum Working Temperature	+840° F
Color	Gold

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End Mills

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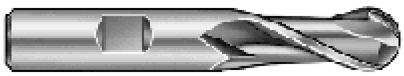

8770A851

Each

In stock for $13.58

Type	Ball End
Ball-End End Mill Type	General Purpose
End Mill Material	Solid Carbide
Solid Carbide Material Type	Premium Sub-Micrograin
Coating	TiN
Number of Flutes	Three Flute
Single or Double End	Single
End Style	Center Cutting
Mill Diameter	1/8"
Mill Diameter Tolerance	+.000", -.002"
Shank Diameter	1/8"
Length of Cut	1/2"
Overall Length	1-1/2"
Helix Angle	30°
Maximum Working Temperature	+840° F
Color	Gold

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End Mills

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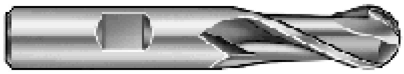

8770A871

Each

In stock for $24.35

Type	Ball End
Ball-End End Mill Type	General Purpose
End Mill Material	Solid Carbide
Solid Carbide Material Type	Premium Sub-Micrograin
Coating	TiN
Number of Flutes	Three Flute
Single or Double End	Single
End Style	Center Cutting
Mill Diameter	1/4"
Mill Diameter Tolerance	+.000", -.002"
Shank Diameter	1/4"
Length of Cut	3/4"
Overall Length	2-1/2"
Helix Angle	30°
Maximum Working Temperature	+840° F
Color	Gold

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End Mills

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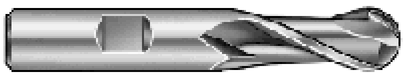

8795A821

Each

In stock for $15.05

Type	Ball End
Ball-End End Mill Type	General Purpose
End Mill Material	Solid Carbide
Solid Carbide Material Type	Premium Sub-Micrograin
Coating	TiN
Number of Flutes	Two Flute
Single or Double End	Single
End Style	Center Cutting
Mill Diameter	1/16"
Mill Diameter Tolerance	+.000", -.002"
Shank Diameter	1/8"
Length of Cut	3/16"
Overall Length	1-1/2"
Helix Angle	30°
Maximum Working Temperature	+840° F
Color	Gold

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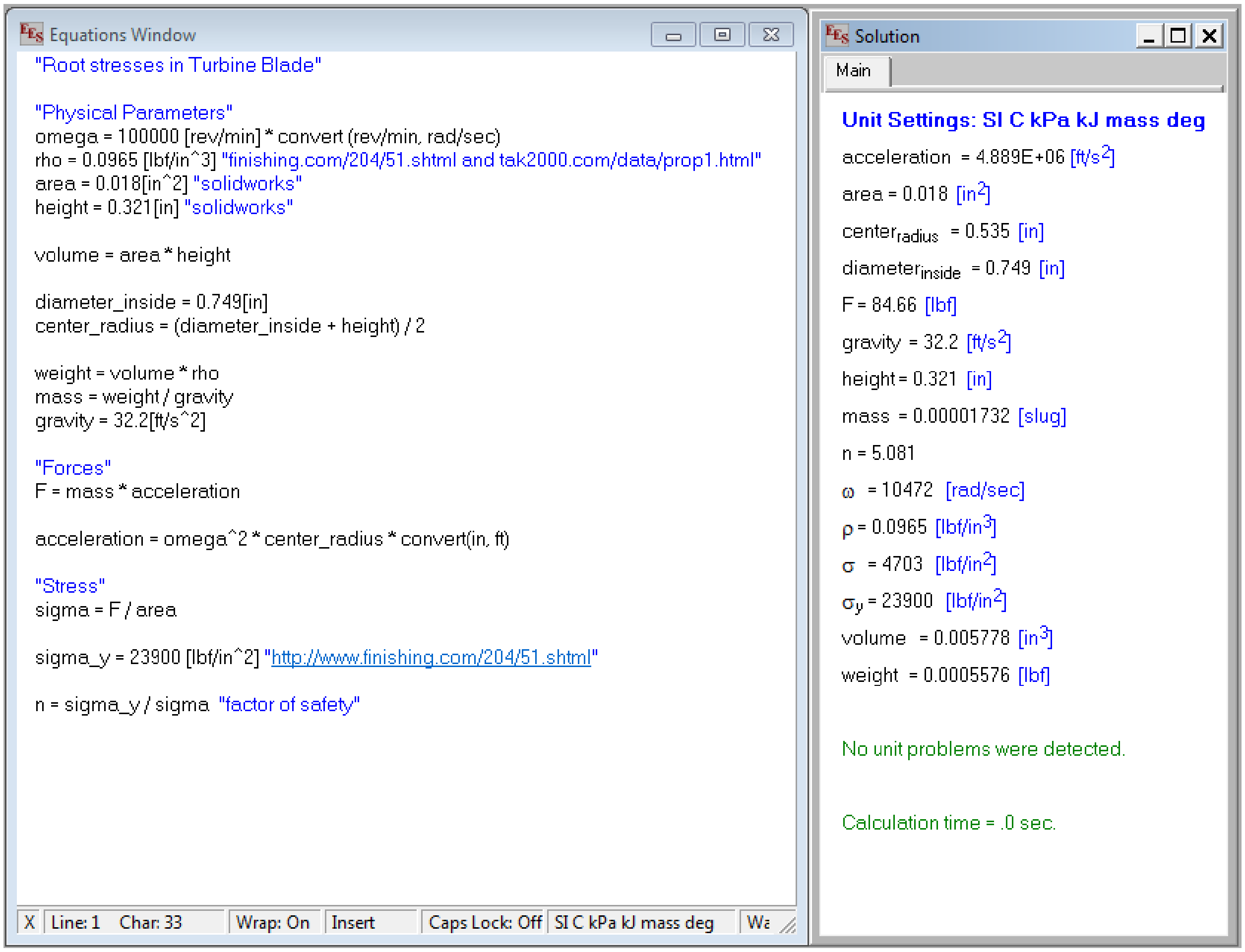
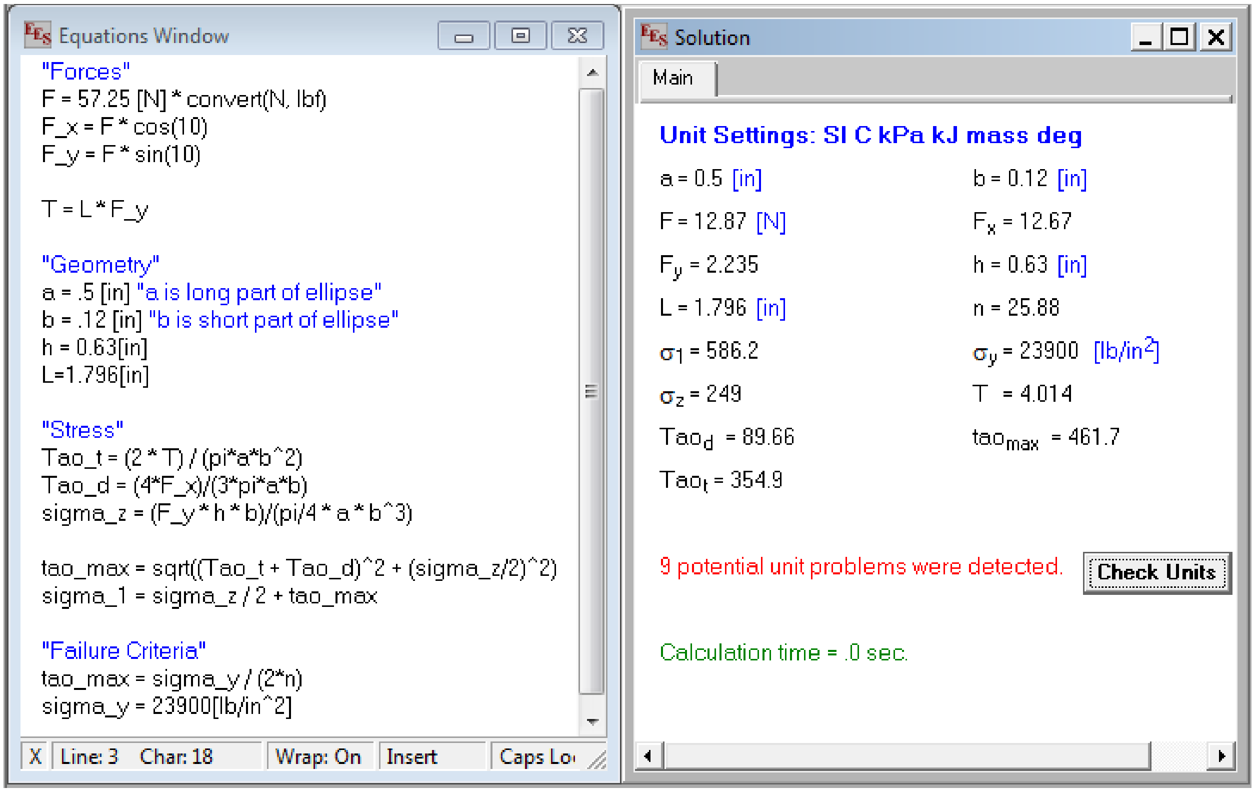
Appendix E: Detailed Supporting Analysis

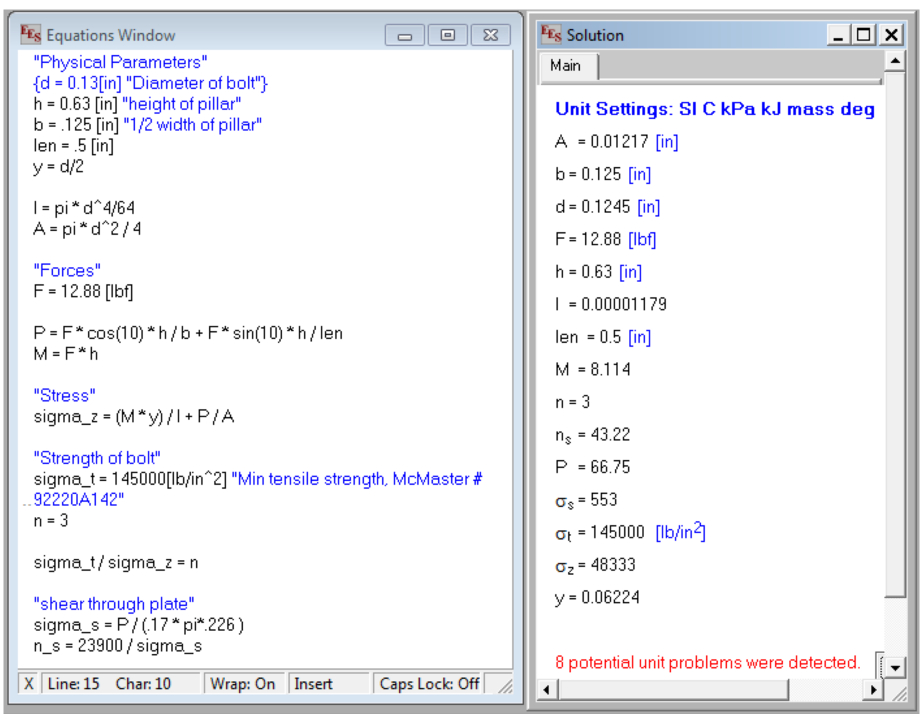
Calculations of Root Stress on Turbine Blade using EES



Calculation of Nacelle Strut Safety Factor using EES



Calculation of Minimum Bolt Diameter



Calculation of Drag Forces (5 Pages)

- Find Reynolds number:

$$Re = \frac{\rho \bar{V} D}{\mu}$$

@ 50,000 ft = 15240 m ← use table value of 15,000 m

from table in Fluid Mechanics 6th Edition by Robert W. Fox

15,000 m	$T = 216.7\ K$	$P/P_{SL} = 0.1195$	$\rho/\rho_{SL} = .1590$

$P_{SL} = 1.01326 \times 10^5\ Pa = 14.696\ psia$

$\rho_{SL} = 1.2250\ kg/m^3 = 0.002377\ slug/ft^3$

Table A.3 of Fox (P. 719)

$\rho = .1590\ \rho_{SL} = .1590(1.2250)$

$\boxed{\rho = .194775\ kg/m^3}$

$P = 0.1195\ P_{SL} = 0.1195(1.01326 \times 10^5\ Pa)$

$\boxed{P = 1210.83375\ Pa}$

from equation A.1 on P 721 of Fox:

$$\mu = \frac{b T^{1/2}}{1 + S/T} = \frac{b T^{3/2}}{S + T}$$

with $b = 1.458 \times 10^{-6} \frac{kg}{m \cdot s \cdot K^{1/2}}$

$S = 110.4\ K$

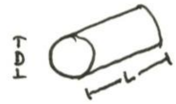
$$\mu = \frac{\left(1.458 \times 10^{-6} \frac{kg}{m \cdot s \cdot K^{1/2}}\right)(216.7\ K)^{3/2}}{110.4\ K + 216.7\ K}$$

$\boxed{\mu = 1.42189 \times 10^{-5} \frac{kg}{m \cdot s}}$

$\boxed{\bar{V} = 350\ ft/s = 106.68\ m/s}$ ← given from operating conditions

$$Re = \frac{\rho \bar{V} D}{\mu} = \frac{(.194775)(106.68) D}{1.42189 \times 10^{-5}}$$

$\boxed{Re = 1461338.7 D}$ ← where D is in meters look @ Turbine in 2 configurations:



$D = 1.36'' = .03429\ m$

$L = 2.25'' = .0579\ m$

inline flow:

normal flow

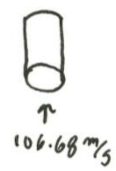
$Re = 1461338.7(.03429)$

$\boxed{Re = 50{,}109.3}$

$Re = 1461338.7(.0579)$

$\boxed{Re = 84{,}611.5}$

- Find Pressure drag for inline flow



approximate turbine as flow over a disk 

for $Re \geq 10{,}000$ $\quad C_D = 1.17$ (P. 489 - Fox)

$$F_D = C_D A \tfrac{1}{2} \rho V^2$$

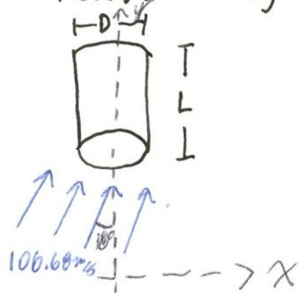
$$F_D = C_D \tfrac{1}{2}\pi\left(\tfrac{D}{2}\right)^2 \rho V^2$$

$$F_D = 1.17(.5)(.25)\pi D^2(.194775)(106.68)^2$$

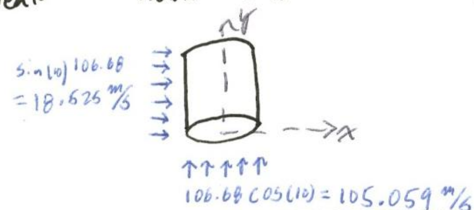
$F_D = 1018.46 D^2$ Newtons where D is in meters

Calculations performed on 12/-20 to find forces turbine will experience due to drag (continued) KL

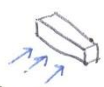
- find pressure drag for 10° offset flow



break down into x & y components



$$F_D = \sqrt{\left[C_D A \tfrac{1}{2} \rho V^2\right]_x^2 + \left[C_D A \tfrac{1}{2} \rho V^2\right]_y^2}$$

- Approximate flow in x direction as flow over a square prism  from FOX C_D for square prism ranges from 1.05 - 2.05 chose ~~choose~~ 2.05 to get worst case results.
- For flow in y direction model flow as flow over a disk $C_D = 1.17$

$$F_D = \sqrt{\left[(2.05)(LD)(\tfrac{1}{2})(.194775)(18.525)^2\right]_x^2 + \left[(1.17)\pi\left(\tfrac{D}{2}\right)^2(\tfrac{1}{2})(.194775)(105.059)^2\right]_y^2}$$

$$F_D = \sqrt{(68.513 DL)^2 + (987.746 D^2)^2}$$

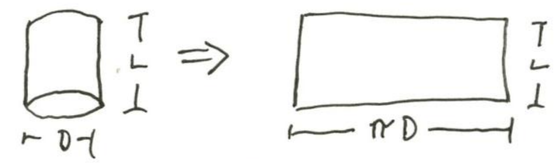
with $D = .0342\ m$
$L = .0579\ m$

$$\boxed{F_D = 1.16 \text{ Newtons}}$$

Calculations performed on 12/20 to find forces turbine will experience due to drag (continued) KZ

- find friction drag

get ball park number by treating turbine as a flat plate with same area that would be from a rolled out cylinder:



since $Re > 1{,}000$ for our case use fig 9.10 (from Fox) and and get $C_D \approx 1.1$

$$F_D = (1.1)(L\pi D)(\tfrac{1}{2})(\rho)(V^2)$$

$$F_D = 3830.115LD \quad \leftarrow \text{w/ } L \,\&\, D \text{ in meters}$$

$$\boxed{F_D = 7.604 \text{ Newtons}}$$

Therefore worst case Drag @ 50,000 ft = friction drag + Pressure drag ≈ 10 Newtons

· Ran same calculations w/ ρ_{SL} to see drag forces @ takeoff and landing

w/ $\rho_{SL} = 1.2250\ kg/m^3$, $D = .03429$, $L = .0579$

Pressure drag head on	Pressure drag 10° offset	friction drag
$F_D = 6405.424D^2$	$F_D = \sqrt{(430.90DL)^2 + (6224.074D^2)^2}$	$F_D = 24088.77LD$
$F_D = 9.4226$ Newtons	$F_D = 7.368$ Newtons	$F_D = 47.83$ N

∴ worst case scenario is pressure and friction drag acting @ Sea level putting a total drag force of $\boxed{57.25 \text{ Newtons}}$

Max thrust force that generator will experience from the rotor is $\boxed{9.42 \text{ Newtons}}$ or $6405.424D^2$

Calculations of Thermal Expansion Effects

Calculation performed on 12/23 to determine change in size of cowling ~~k2~~

for unrestrained body

$$\varepsilon_x = \varepsilon_y = \varepsilon_z = \alpha \Delta T$$

equation 3-60 on p. 111 of Shigley's Mechanical Engineering and Design 8th Edition

~~[illegible]~~

$$\Delta T = 20°C - (-60°C)$$

↑ currently BCPS has total failure @ -56°C

$$\Delta T = 80°C$$

For 356 Aluminum:

$$\alpha = 21.5 \frac{m \times 10^{-12}}{m K}$$ ← number gotten from hadliegh castings.com/uploads/A356%20Alloy%20Detail.Pdf

for 20-100°C

↑ okay for this initial calculation but would like a number for -60-20 °C

$$D_g = .632 \text{ in} \left(\frac{2.54 \text{ cm}}{\text{in}}\right)\left(\frac{m}{100 \text{ cm}}\right) = .016 \text{ m}$$

$$\varepsilon_{D_g} = (21.5)\frac{m \times 10^{-12}}{m K}(80 K) = 1720 \frac{m \times 10^{-12}}{m} = \frac{1.72 \times 10^{-9} m}{m}$$

D_g will vary by $D_g \varepsilon_{D_g} = 2.752 \times 10^{-11}$ m from initial temperature to final temperature assuming thermal expansion coefficient is accurate

Calculations of Support Strut Safety Factor

$$M = F \times d$$

$$T = F \times c$$

$$\sigma_x = \frac{Mc}{I_x}$$

$$\tau = \frac{Tr}{J}$$

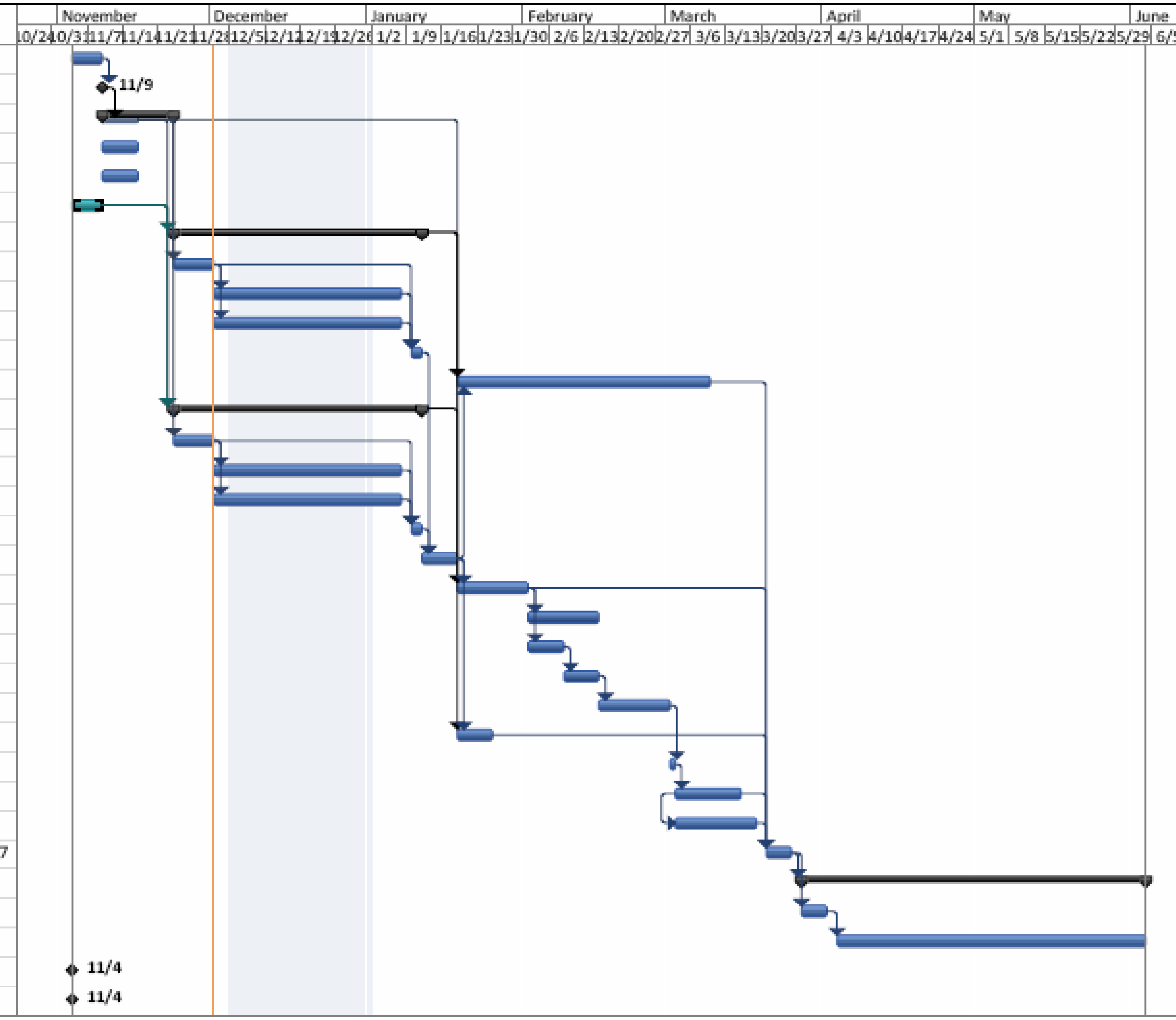
$$\sigma' = \sqrt{\sigma_x^2 + 3\tau^2}$$

$$\eta = \frac{S_y}{\sigma'}$$

Height of Strut (inch)	Width of Strut (in)	Ix (in^4)	Iy (in^4)	J (in^4)	r (in)	M (lb_f*in)	T (lbf*in)	σ_x (lb_f/in^2)	τ (lb_f/in^2)	Distortion-Energy Theory (lb_f/in^2)	Factor of Safety
0.1	1.0	0.0359	0.0015	0.0374	0.625	10.940	8.366	198.1	139.8	312.8	76.39
0.2	1.0	0.0359	0.0015	0.0374	0.625	12.227	8.366	221.4	139.8	328.1	72.84
0.3	1.0	0.0359	0.0015	0.0374	0.625	13.514	8.366	244.7	139.8	344.2	69.43
0.4	1.0	0.0359	0.0015	0.0374	0.625	14.801	8.366	268.0	139.8	361.2	66.17
0.5	1.0	0.0359	0.0015	0.0374	0.625	16.088	8.366	291.3	139.8	378.8	63.10
0.6	1.0	0.0359	0.0015	0.0374	0.625	17.375	8.366	314.6	139.8	397.0	60.20
0.7	1.0	0.0359	0.0015	0.0374	0.625	18.662	8.366	337.9	139.8	415.7	57.49
0.8	1.0	0.0359	0.0015	0.0374	0.625	19.949	8.366	361.2	139.8	434.8	54.96
0.9	1.0	0.0359	0.0015	0.0374	0.625	21.236	8.366	384.5	139.8	454.4	52.60
1.0	1.0	0.0359	0.0015	0.0374	0.625	22.523	8.366	407.8	139.8	474.3	50.39
0.5	0.1	0.0006	0.0003	0.0009	0.175	16.088	8.366	17550.0	1595.1	17766.1	1.35
0.5	0.2	0.0014	0.0005	0.0018	0.225	16.088	8.366	7631.4	1032.8	7838.3	3.05
0.5	0.3	0.0026	0.0006	0.0032	0.275	16.088	8.366	3960.8	713.9	4149.3	5.76
0.5	0.4	0.0045	0.0007	0.0052	0.325	16.088	8.366	2308.2	518.6	2476.8	9.65
0.5	0.5	0.0072	0.0008	0.0080	0.375	16.088	8.366	1459.2	391.7	1609.2	14.85
0.5	0.6	0.0107	0.0010	0.0116	0.425	16.088	8.366	979.8	305.3	1113.4	21.47
0.5	0.7	0.0152	0.0011	0.0163	0.475	16.088	8.366	689.1	244.1	808.5	29.56
0.5	0.8	0.0208	0.0012	0.0220	0.525	16.088	8.366	502.8	199.4	610.0	39.18
0.5	0.9	0.0277	0.0014	0.0290	0.575	16.088	8.366	378.0	165.7	474.6	50.36
0.5	1.0	0.0359	0.0015	0.0374	0.625	16.088	8.366	291.3	139.8	378.8	63.10

Appendix F: GANNT Chart

ID		Task Mode	Task Name	Duration	Start	Finish	Predecessors
1			Build conceptual model	4 days	Thu 11/4/10	Tue 11/9/10	
2			Conceptual model due	0 days	Tue 11/9/10	Tue 11/9/10	1
3			**Manufacturable concept model**	**10 days**	**Wed 11/10/10**	**Tue 11/23/10**	**2**
4			Contact CNC/Manufacturing experts	5 days	Wed 11/10/10	Tue 11/16/10	
5			Make solid Model	5 days	Wed 11/10/10	Tue 11/16/10	
6			Material Selection	4 days	Thu 11/4/10	Tue 11/9/10	
7			**Design cowling**	**14 days**	**Wed 11/24/10**	**Tue 1/11/11**	**6**
8			drag analysis	6 days	Wed 11/24/10	Wed 12/1/10	3
9			Stress analysis	6 days	Thu 12/2/10	Fri 1/7/11	8
10			Fatigue Analysis	6 days	Thu 12/2/10	Fri 1/7/11	8
11			Make Solid Model	2 days	Mon 1/10/11	Tue 1/11/11	8,9,10
12			Manufacture cowling	36 days	Wed 1/19/11	Wed 3/9/11	7,18
13			**Design support**	**14 days**	**Wed 11/24/10**	**Tue 1/11/11**	**3,6**
14			drag analysis	6 days	Wed 11/24/10	Wed 12/1/10	3
15			Stress analysis	6 days	Thu 12/2/10	Fri 1/7/11	14
16			Fatigue Analysis	6 days	Thu 12/2/10	Fri 1/7/11	14
17			Make Solid Model	2 days	Mon 1/10/11	Tue 1/11/11	14,15,16
18			Purchase Materials	5 days	Wed 1/12/11	Tue 1/18/11	11,17
19			Manufacture Turbine blisk	10 days	Wed 1/19/11	Tue 2/1/11	3,18,7
20			Rotor testing/balancing	10 days	Wed 2/2/11	Tue 2/15/11	19
21			select desired generator	5 days	Wed 2/2/11	Tue 2/8/11	19
22			purchase generator	5 days	Wed 2/9/11	Tue 2/15/11	21
23			wind tunnel / find heater resistance	10 days	Wed 2/16/11	Tue 3/1/11	22
24			Manufacture Support	5 days	Wed 1/19/11	Tue 1/25/11	13,18
25			Select Heater	1 day	Wed 3/2/11	Wed 3/2/11	23
26			Purchase Heater	8 days	Thu 3/3/11	Tue 3/15/11	25
27			Purchase controller	11 days	Thu 3/3/11	Fri 3/18/11	26SS
28			Assemble prototype	5 days	Mon 3/21/11	Fri 3/25/11	19,12,24,26,27
29			**test prototype**	**50 days**	**Mon 3/28/11**	**Fri 6/3/11**	**28**
30			Wind tunnel test	5 days	Mon 3/28/11	Fri 4/1/11	28
31			Evaluation/Revision/Full scale test	45 days	Mon 4/4/11	Fri 6/3/11	30
32			Online Reflection Due	0 days	Thu 11/4/10	Thu 11/4/10	
33			Conceptual Design Report Due	0 days	Thu 11/4/10	Thu 11/4/10	



Project: IcePick Gannt chart
Date: Thu 12/2/10

Task		Project Summary		Inactive Milestone		Manual Summary Rollup		Deadline	
Split		External Tasks		Inactive Summary		Manual Summary		Progress	
Milestone		External Milestone		Manual Task		Start-only			
Summary		Inactive Task		Duration-only		Finish-only			

Appendix G: Design Verification Plan and Testing Procedures

Design Verification Planning and Report

ME428/ME481 DVP&R Format													
Report Date			Sponsor:	Professor Westhpal					BLDS Heater			REPORTING ENGINEER: Alan Cook	
TEST PLAN										TEST REPORT			
Item	Specification or	Test Description	Acceptance Criteria	Test Resonsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Weight	Put entire assembly on scale	≤ 1.0lb	Alan Cook	PV	1	C						
2	Power Output/Strip Heater Resistance	Place turbine in wind tunnel, measure power output of turbine at operating wind speed (or max wind speed @ Cal Poly) vary resistance to get max power output.	Any resistance is acceptable as long as the generator's output is ≥ 50 Watts	Jon Hsu	DV	1	B						
3	Coefficient of Expansion	Measure OD of generator body and shaft, and ID of nacelle and blisk at room temperature. Put in freeze chamber and measure new respective ODs and IDs	ΔØ ≤ -0.0005 in	Robert Veasey	PV	1	C						
4	Time to mount	Mount on simulated wing. Measure time to completion	≤ 1.0 hour	Alan Cook & Jon Hsu	DV	1	B						
5	Generator Operation	Put generator in freeze chamber and spin with die grinder. Measure power output of generator	≥ 50 Watts	Robert Veasey	PV	1	C						
6	Vibration Test	Run generator with full assembly mounted on shake table with white noise input.	No dynamic interference between blisk and cowling or failure of parts is acceptable	Alan Cook	PV	1	C						

Detailed Experiments, Procedures, and Materials Needed

Specification:		Power Output/Strip Heater Resistance
Test Description:		Place turbine in wind tunnel, measure power output of turbine at operating wind speed vary resistance to get max power output.
Materials/Parts Needed:	1.)	Ahmeter
	2.)	Ohmmeter
	3.)	Large Decade Box (to dissipate heat)
	4.)	Jumpers
	5.)	Banana plugs
	6.)	Extra wire to run out of the wind tunnel
	7.)	Tape to keep wire from flapping in the windtunnel
	8.)	Pitot static probe and pressure transducer
	9.)	Barometer
	10.)	Themometer
Procedure:	1.)	Wire decade box, ahmeter and generator as shown in the schematic
	2.)	Make sure wires are taped down so they will not come loose when wind tunnel is turned on
	3.)	Check windtunnel to ensure that there is nothing that will get blown out of the windtunnel
	4.)	Mount turbine in test section
	5.)	Record ambient pressure and temperature
	6.)	Turn on the wind tunnel and ramp up to 350 ft/s or if 350 ft/s is unachievable, ramp up to max speed
	7.)	Use Pitot static probe and pressure transducer to record free stream velocity upstream of turbine and verify that the windtunnel is operating at steady state
	8.)	Using the decade box vary resistances from 0 Ω to 5000Ω and measure current output from the generator, verify resistances with ohmmeter
	9.)	Ramp down the windspeed and shut off the windtunnel
	10.)	Clean up materials and plot power output against resistance and extropolate results if wind speed is not 350 ft/s
Measurements Recorded:	1.)	Ambient Pressure
	2.)	Amibent Temperature
	3.)	Free stream velocity
	4.)	Table of resistances and corresponding current output

Specification:		Weight
Test Description:		Put entire assembly on scale
Materials/Parts Needed:	1.)	Fully assembled BLDS heater
	2.)	Scale
Procedure:	1.)	Assemble complete BLDS heater
	2.)	Place on scale and record weight
Measurements Recorded:	1.)	Weight

Specification:		Coefficient of Expansion
Test Description:		Measure OD of generator body and shaft, and ID of nacelle and blisk at room temperature. Put in freeze chamber and measure new respective ODs and IDs
Materials/Parts Needed:	1.)	Freeze Chamber
	2.)	Generator
	3.)	Nacelle
	4.)	Blisk
	5.)	Cowling
	6.)	Calipers
	7.)	Die grinder
	8.)	Thermometer
Procedure:	1.)	Record temperature of ambient air
	2.)	Measure generator body and shaft OD
	3.)	Measure Nacelle's ID
	4.)	Measure blisk ID and OD
	5.)	Measure Cowling ID
	6.)	Put generator,nacelle, blisk and cowling in freeze chamber until parts have reached -60°C
	7.)	Repeate steps 2-5 and with parts at -60 C
Measurements Recorded:	1.)	Critical dimensions of parts at ambient temperature and at -60 C

Specification:		Time to mount
Test Description:		Mount on simulated wing, measure time to completion
Materials/Parts Needed:	1.)	Fully assembled BLDS heater
	2.)	Stopwatch
	3.)	Simulated wing (aluminum plate)
Procedure:	1.)	Assemble BLDS heater
	2.)	Mount on simulated wing and record time to completion
Measurements Recorded:	1.)	Time to mount

Specification:		Generator Operation
Test Description:		Put generator in freeze chamber and spin with die grinder. Measure power output of generator
Materials/Parts Needed:	1.)	Freeze Chamber
	2.)	Die Grinder
	3.)	Generator
	4.)	Ahmeter
	5.)	Ohmmeter
	6.)	Large Decade Box (to dissipate heat)
	7.)	Jumpers
	8.)	Banana plugs
Procedure	1.)	Place generator in freeze chamber unitl temperature reaches -60 C
	2.)	Pull out generator and wire as shown in the schematic
	3.)	Spin generator with die grinder and record power output
Measurements Recorded:	1.)	Power ouput at -60 C

Appendix H: Generator Selection Chart

Generator Selection

All Brushless DC motors supplied by Maxon with a diameter ≤ 16mm were considered for use as generator. Decision was performed by Team IcePick on 01/13/2011

6mm, 1.2 Watt #250101	
Diameter	6 mm
Power Output	1.2W
Weight	2.8 g
Max rpm	100,000
Max Axial Load	0.1 N

13mm, 12 Watt #305197	
Diameter	13 mm
Power Output	12 W
Weight	25 g
Max rpm	50,000
Max Axial Load	1.0 N

16mm, 40 Watt #235689	
Diameter	16 mm
Power Output	40 W
Weight	58 g
Max rpm	50,000
Max Axial Load	3.0 N

8mm, 2 Watt #384410	
Diameter	8 mm
Power Output	2 W
Weight	6.0g
Max rpm	80,000
Max Axial Load	0.1 N

13mm, 30 Watt #371407	
Diameter	13 mm
Power Output	30 W
Weight	34 g
Max rpm	90,000
Max Axial Load	2.0 N

16mm, 40 Watt #235823	
Diameter	16 mm
Power Output	40 W
Weight	58 g
Max rpm	50,000
Max Axial Load	3.0 N

10mm, 8 Watt #315176	
Diameter	10 mm
Power Output	8 W
Weight	13 g
Max rpm	80,000
Max Axial Load	1.0 N

13mm, 50 Watt #384215	
Diameter	13 mm
Power Output	50 W
Weight	44 g
Max rpm	90,000
Max Axial Load	2.0 N

13mm, 6 Watt #318002	
Diameter	13 mm
Power Output	6 W
Weight	15 g
Max rpm	50,000
Max Axial Load	1.0 N

16mm, 15 Watt #266523	
Diameter	16 mm
Power Output	15 W
Weight	34 g
Max rpm	50,000
Max Axial Load	3.0 N

All generators were compared against design specifications outlined below. Generator specifications which have green backrounds met or exceeded our design requirements. Red backgrounds indicate specifications which didn't meet our design requirements. Team AeroRat's power output for their generator was used as a minimum for our requirements. Max rpm was made based on the max speed the blisk will get up to under no load. Max axial load was based off of drag analysis performed. It is unlikely that the plane will be at it's maximum cruising speed while at sealevel so the drag at cruising speed and altitude was selected as a design requirement for axial load.

Desired Specifications	
Diameter	≤ 16mm
Power Output	≥40 Watts
Weight	≤0.5lb=113g
Max rpm	≥83,000
Max Axial Load	9.42 N @ 350 ft/s @ sealevel
	1.198 N @ 350ft/s @ sealevel

Appendix I: Raw Testing Data

Testing Data for First Test

Date: 4/22/2011
Patm: 100.64 kpa
Tatm: 21.63 °C
Pzero: 0.005

				Resistance					
Fan Speed (Hz)	Pitot-Static Pressure (in H20)	Pitot-Static Pressure (lbf/ft2)	Test Speed (ft/s)	1	2	3	Volts$_{P-P}$ (V)	Frequency (Hz)	Power (Watts)
20	0.654	3.38	54.2	17.7	15.3	17.2	0.250	62.5	0.005
25	1.027	5.31	68.0	17.7	15.3	17.2	0.400	99.0	0.014
30	1.473	7.62	81.4	17.7	15.3	17.2	0.576	142.5	0.028
35	2.020	10.45	95.3	17.7	15.3	17.2	0.776	188.7	0.051
40	2.662	13.77	109.4	17.7	15.3	17.2	1.000	242.7	0.085
45	3.400	17.59	123.7	17.7	15.3	17.2	1.160	301.2	0.114
50	4.208	21.77	137.6	17.7	15.3	17.2	1.420	357.0	0.171

				Resistance					
Fan Speed (Hz)	Pitot-Static Pressure (in H20)	Pitot-Static Pressure (lbf/ft2)	Test Speed (ft/s)	1	2	3	Volts$_{P-P}$ (V)	Frequency (Hz)	Power (Watts)
20	0.598	3.09	51.9	30.5	31.5	29.6	0.316	75.0	0.005
25	0.980	5.07	66.4	30.5	31.5	29.6	0.500	123.5	0.012
30	1.444	7.47	80.6	30.5	31.5	29.6	0.712	170.0	0.025
35	2.000	10.35	94.9	30.5	31.5	29.6	0.936	232.2	0.043
40	2.649	13.71	109.2	30.5	31.5	29.6	1.180	284.0	0.068
45	3.382	17.50	123.4	30.5	31.5	29.6	1.460	347.2	0.105
50	4.200	21.73	137.5	30.5	31.5	29.6	1.700	403.0	0.142

				Resistance					
Fan Speed (Hz)	Pitot-Static Pressure (in H20)	Pitot-Static Pressure (lbf/ft2)	Test Speed (ft/s)	1	2	3	Volts$_{P-P}$ (V)	Frequency (Hz)	Power (Watts)
20	0.598	3.09	51.9	40	39.3	41	0.388	90.0	0.006
25	0.983	5.09	66.5	40	39.3	41	0.616	147.0	0.014
30	1.445	7.48	80.6	40	39.3	41	0.880	208.0	0.029
35	2.001	10.35	94.9	40	39.3	41	1.110	272.0	0.046
40	2.649	13.71	109.2	40	39.3	41	1.370	331.0	0.070
45	3.385	17.52	123.4	40	39.3	41	1.640	403.2	0.101
50	4.196	21.71	137.4	40	39.3	41	1.940	459.0	0.141

Testing Data for Second Test:

Fan Speed (Hz)	Pitot-Static Pressure (in H20)	Pitot-Static Pressure (lbf/ft2)	Test Speed (ft/s)	Average Test Speed (ft/s)
20	0.641	3.32	53.7	53.7
	0.638	3.30	53.6	
	0.640	3.31	53.7	
	0.641	3.32	53.7	
	0.639	3.31	53.6	
30	1.488	7.70	81.8	81.8
	1.490	7.71	81.9	
	1.487	7.69	81.8	
	1.483	7.67	81.7	
	1.487	7.69	81.8	
40	2.669	13.81	109.6	109.7
	2.672	13.83	109.7	
	2.670	13.82	109.6	
	2.673	13.83	109.7	
	2.676	13.85	109.7	
50	4.462	23.09	141.7	137.8
	4.159	21.52	136.8	
	4.160	21.53	136.8	
	4.157	21.51	136.8	
	4.159	21.52	136.8	
60	5.924	30.65	163.3	163.2
	5.914	30.60	163.1	
	5.915	30.61	163.1	
	5.926	30.66	163.3	
	5.916	30.61	163.2	

Fan Speed (Hz)	Current (A)	Voltage (V)	Resistance, calculated (Ω)	Power (Watts)
30	0.2560	0.597	2.33	0.1528
	0.2120	2.204	10.40	0.4672
	0.1370	4.490	32.77	0.6151
	0.1170	5.430	46.41	0.6353
	0.1120	5.600	50.00	0.6272
	0.1010	6.010	59.50	0.6070
	0.0920	6.330	68.80	0.5824
	0.0842	6.610	78.50	0.5566
	0.0767	6.840	89.18	0.5246
	0.0700	7.080	101.14	0.4956
40	0.5110	0.944	1.85	0.4824
	0.3970	4.330	10.91	1.7190
	0.2790	7.680	27.53	2.1427
	0.2340	8.880	37.95	2.0779
	0.2010	9.920	49.35	1.9939
	0.1810	10.400	57.46	1.8824
	0.1680	11.140	66.31	1.8715
	0.1480	11.370	76.82	1.6828
	0.1320	11.740	88.94	1.5497
	0.1230	12.280	99.84	1.5104
50	0.5910	1.120	1.90	0.6619
	0.6880	6.030	8.76	4.1486
	0.4750	11.280	23.75	5.3580
	0.3850	12.960	33.66	4.9896
	0.3108	14.280	45.95	4.4382
	0.2680	15.150	56.53	4.0602
	0.2390	15.900	66.53	3.8001
	0.2130	16.320	76.62	3.4762
	0.1900	17.060	89.79	3.2414
	0.1780	17.280	97.08	3.0758
60	1.2700	2.350	1.85	2.9845
	0.9000	10.060	11.18	9.0540
	0.6400	15.200	23.75	9.7280
	0.5130	17.300	33.72	8.8749
	0.3930	19.340	49.21	7.6006
	0.3420	20.020	58.54	6.8468
	0.3110	20.610	66.27	6.4097
	0.2640	21.230	80.42	5.6047
	0.2420	21.700	89.67	5.2514
	0.2190	22.070	100.78	4.8333

Testing Data for Third Test

Fan Speed (Hz)	Pitot-Static Pressure (in H20)	Test Speed (ft/s)	Average Test Speed (ft/s)	Test Seed Uncertainty		Dynamic Pressure (psi)	Average Dynamic Pressure	Dynamic Pressure Uncertainty
30	1.488	81.5	81.5	1.07759		0.0535	0.0535	3.0479
	1.490	81.6		1.07759		0.0536		3.0479
	1.487	81.5		1.07759		0.0535		3.0479
	1.483	81.4		1.07759		0.0533		3.0479
	1.487	81.5		1.07759		0.0535		3.0479
40	2.669	109.2	109.2	1.07759		0.0960	0.0961	3.0479
	2.672	109.2		1.07759		0.0961		3.0479
	2.670	109.2		1.07759		0.0960		3.0479
	2.673	109.2		1.07759		0.0961		3.0479
	2.676	109.3		1.07759		0.0962		3.0479
50	4.462	141.1	137.2	1.07759		0.1605	0.1517	3.0479
	4.159	136.3		1.07759		0.1496		3.0479
	4.160	136.3		1.07759		0.1496		3.0479
	4.157	136.2		1.07759		0.1495		3.0479
	4.159	136.3		1.07759		0.1496		3.0479
60	5.924	162.6	162.6	1.07759		0.2131	0.2129	3.0479
	5.914	162.5		1.07759		0.2127		3.0479
	5.915	162.5		1.07759		0.2127		3.0479
	5.926	162.7		1.07759		0.2131		3.0479
	5.916	162.5		1.07759		0.2128		3.0479

Fan Speed (Hz)	Current (A)	Voltage (V)	Resistance, calculated (Ω)	Power (Watts)
30	0.4300	0.880	2.05	0.3784
	0.3200	2.200	6.88	0.7040
	0.2200	3.000	13.64	0.6600
	0.1500	3.500	23.33	0.5250
	0.1120	5.600	50.00	0.6272
	0.1010	6.010	59.50	0.6070
	0.0920	6.330	68.80	0.5824
	0.0842	6.610	78.50	0.5566
	0.0767	6.840	89.18	0.5246
	0.4300	0.880	2.05	0.3784
40	0.5110	0.944	1.85	0.4824
	0.3970	4.330	10.91	1.7190
	0.2790	7.680	27.53	2.1427
	0.2340	8.880	37.95	2.0779
	0.2010	9.920	49.35	1.9939
	0.1810	10.400	57.46	1.8824
	0.1680	11.140	66.31	1.8715
	0.1480	11.370	76.82	1.6828
	0.1320	11.740	88.94	1.5497
	0.1230	12.280	99.84	1.5104
50	0.5910	1.120	1.90	0.6619
	0.6880	6.030	8.76	4.1486
	0.4750	11.280	23.75	5.3580
	0.3850	12.960	33.66	4.9896
	0.3108	14.280	45.95	4.4382
	0.2680	15.150	56.53	4.0602
	0.2390	15.900	66.53	3.8001
	0.2130	16.320	76.62	3.4762
	0.1900	17.060	89.79	3.2414
	0.1780	17.280	97.08	3.0758
60	1.2700	2.350	1.85	2.9845
	0.9000	10.060	11.18	9.0540
	0.6400	15.200	23.75	9.7280
	0.5130	17.300	33.72	8.8749
	0.3930	19.340	49.21	7.6006
	0.3420	20.020	58.54	6.8468
	0.3110	20.610	66.27	6.4097
	0.2640	21.230	80.42	5.6047
	0.2420	21.700	89.67	5.2514
	0.2190	22.070	100.78	4.8333

Appendix J: References

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